VERIFICATION OF RAMPS SOFTWARE

FOR DESIGN OF STEEL I-GIRDERS

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

Fall 2015

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ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Dennis Mertz, for providing me with the opportunity to work with him on this research project. All of his help, guidance, and insights were extremely valuable.

I must also give special thanks to Dr. Frank Moon, Nick Romano, Dave Masceri, and John Bradley. Without their help, none of this would have been possible.

The research presented in this document was funded by the National Cooperative Highway Research Program, specifically Project 12-103.

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A	area of the cross-section of non-composite beam (in.^{2})
b_c	width of steel compression flange used to determine plastic moment (in.)
b_{eff}	effective flange width corresponding to the particular position of the section of interest in the span as specified in Figure 4.6.2.6.2-1 (in.)
b_f	width of steel flange (in.)
b_s	width of concrete flange used to determine plastic moment (in.)
b_t	width of steel tension flange used to determine plastic moment (in.)
D	clear distance of web between girder flanges (in)
dc	distance from the plastic neutral axis to the midthickness of the compression flange used to compute the plastic moment (in.)
D_{cp}	depth of web in compression at the plastic moment determined as specified in Article D6.3.2 in the AASHTO LRFD Specification (in.)
d_e	horizontal distance from the centerline of the exterior girder web at deck level to the interior edge of curb or traffic barrier (ft)
DF	live load moment distribution factor (lanes/girder)
DF_{EXT1}	moment distribution factor of the exterior girder with one lane loaded (lanes/girder)
DF_{EXT2}	moment distribution factor of the exterior girder with two lanes loaded (lanes/girder)
DF_{INT1}	moment distribution factor of the interior girder with one lane loaded (lanes/girder)
DF_{INT2}	moment distribution factor of the interior girder with two lanes loaded (lanes/girder)
DFV	live load shear distribution factor (lanes/girder)

$\mathbf{DFV_{EXT1}}$	shear distribution factor of the exterior girder with one lane loaded (lanes/girder)
$\mathbf{DFV_{EXT2}}$	shear distribution factor of the exterior girder with two lanes loaded (lanes/girder)
$\mathbf{DFV_{INT1}}$	shear distribution factor of the interior girder with one lane loaded (lanes/girder)
$\mathbf{DFV_{INT2}}$	shear distribution factor of the interior girder with two lanes loaded (lanes/girder)
$\mathbf{DL_{deck}}$	distributed load on a girder caused by the deck dead load (lb/in.)
$\mathbf{DL_{diaphragm}}$	distributed load on a girder caused by the diaphragm dead load (lb/in.)
$\mathbf{DL_{parapet}}$	distributed load on a girder caused by the parapet dead load (lb/in.)
$\mathbf{DL_{stringer}}$	distributed load on a girder caused by the girder dead load (lb/in.)
$\mathbf{D_p}$	distance from the top of the concrete deck to the neutral axis of the composite section at the plastic moment (in.)
$\mathbf{d_s}$	distance from the plastic neutral axis to the midthickness of the concrete deck used to compute the plastic moment (in.)
$\mathbf{D_t}$	total depth of the composite section (in.)
$\mathbf{d_t}$	distance from the plastic neutral axis to the midthickness of the tension flange used to compute the plastic moment (in.)
$\mathbf{d_w}$	distance from the plastic neutral axis to the middepth of the web flange used to compute the plastic moment (in.)
$\mathbf{e}$	correction factor
$\mathbf{E_c}$	modulus of elasticity of concrete (ksi)
$\mathbf{e_g}$	distance between the centers of gravity of the beam and deck (in.)
$\mathbf{E_s}$	modulus of elasticity of steel (ksi)
$\mathbf{f_{bu}}$	flange stress calculated without consideration of flange lateral bending (ksi)

fc	compression flange stress at the section under consideration due to the Service II loads calculated without consideration of flange lateral bending (ksi)
f'_c	minimum specified 28-day compressive strength of concrete (ksi)
F_{cr}	elastic lateral torsional buckling stress (ksi)
F_{crw}	nominal web bend-buckling resistance
f_f	flange stress at the section under consideration due to the Service II loads
Fn_{neg}	nominal flexural resistance of the section in negative flexure at the design point of interest
F_{nc}	nominal flexural resistance of the compression flange (ksi)
F_{nt}	nominal flexural resistance of the tension flange (ksi)
F_{yc}	specified minimum yield strength of a compression flange (ksi)
F_{yf}	specified minimum yield strength of a flange (ksi)
F_{yr}	compression flange stress at the onset of nominal yielding within the cross-section, including residual stress effects, but not including compression flange lateral bending
F_{yt}	specified minimum yield strength of a tension flange (ksi)
I	moment of inertia of beam (in^4)
I_{lt}	moment of inertia of beam in long-term composite cross-section (in^4)
I_{st}	moment of inertia of beam in short-term composite cross-section (in^4)
I_{yc}	moment of inertia of the compression flange of the steel section about the vertical axis in the plane of the web (in^4)
I_{yt}	moment of inertia of the tension flange of the steel section about the vertical axis in the plane of the web (in^4)
k	bend-buckling coefficient

K_g	Longitudinal stiffness parameter (in^4)
L	Span of beam (ft)
L_b	unbraced length (in.)
L_p	limiting unbraced length to achieve the nominal flexural resistance of RbRhFyc under uniform bending (in.)
L_r	limiting unbraced length to achieve the onset of nominal yielding in either flange under uniform bending with consideration of compression flange residual stress effects (in.)
M_{neg}	maximum negative moment due to the factored loads at the design point of interest
M_{pos}	maximum positive moment due to the factored loads at the design point of interest
MDL_{neg}	maximum negative moment due to the unfactored dead loads at the design point of interest
MDL_{pos}	maximum positive moment due to the unfactored dead loads at the design point of interest
MLL_{neg1}	maximum unfactored and undistributed negative moment due to the live loads at the design point of interest
MLL_{neg2}	maximum unfactored distributed negative moment due to the live loads at the design point of interest
MLL_{pos1}	maximum unfactored and undistributed positive moment due to the live loads at the design point of interest
MLL_{pos2}	maximum unfactored distributed negative moment due to the live loads at the design point of interest
M_n	nominal flexural resistance of the section (kip-in)
Mn_{pos}	nominal flexural resistance of the section in positive flexure at the design point of interest
M_p	plastic moment of the composite section (kip-in)
$MSDL_{neg}$	maximum negative moment due to the unfactored dead loads at the design point of interest
$MSDL_{pos}$	maximum positive moment due to the unfactored dead loads at the design point of interest

$MSDW_{neg}$	maximum negative moment due to the unfactored future wearing surface at the design point of interest
$MSDW_{pos}$	maximum positive moment due to the unfactored future wearing surface at the design point of interest
M_u	moment due to the factored loads (kip-in.)
M_y	yield moment (kip-in.)
n	modular ratio
N_b	number of beams
N_L	number of design lanes as specified in AASHTO LRFD Article 3.6.1.1.1
P_c	plastic stength of steel compression flange used to determine plastic moment (kip)
Φ_f	resistance factor for flexure
P_s	plastic stength of concrete used to determine plastic moment (kip)
P_t	plastic stength of steel tension flange used to determine plastic moment (kip)
P_w	plastic stength of steel web used to determine plastic moment (kip)
R_b	web load-shedding factor
R_h	hybrid factor
r_t	effective radius of gyration for lateral torsional buckling (in.)
S	spacing of beams (ft)
SB_{lt}	long-term composite elastic section modulus with respect to the bottom of the steel I-girder (in^3)
SB_{nc}	noncomposite elastic section modulus with respect to the bottom of the steel I-girder (in^3)

$\mathbf{SB_{st}}$	short-term composite elastic section modulus with respect to the bottom of the steel I-girder (in^3)
$\mathbf{ST_{lt}}$	long-term composite elastic section modulus with respect to the top of the steel I-girder (in^3)
$\mathbf{ST_{nc}}$	noncomposite elastic section modulus with respect to the top of the steel I-girder (in^3)
$\mathbf{ST_{st}}$	short-term composite elastic section modulus with respect to the top of the steel I-girder (in^3)
$\mathbf{t_c}$	thickness of steel compression flange used to determine plastic moment (in.)
$\mathbf{t_f}$	thickness of steel flange (in.)
$\mathbf{t_s}$	Thickness of concrete slab (in)
$\mathbf{t_t}$	thickness of steel tension flange used to determine plastic moment (in.)
$\mathbf{t_w}$	thickness of web (in.)
V	shear due to the factored and distributed loads at the design point of interest (lbs)
VDL	shear due to the unfactored dead loads at the design point of interest (lbs)
VDW	shear due to the unfactored wearing surface loads at the design point of interest (lbs)
VLL	shear due to the live load loads at the design point of interest (lbs)
$\mathbf{V_{cr}}$	shear-buckling resistance (kip)
$\mathbf{V_n}$	nominal shear resistance (kip)
$\mathbf{V_u}$	shear due to the factored loads (kip)
$\mathbf{V_p}$	plastic shear force (kip)
wDL	distributed load as a result of the dead load (lb/in)

wSDL	distributed load as a result of the superimposed dead load (lb/in)
wSDW	Distributed load as a result of the future wearing surface (lb/in)
$\bar{Y}$	distance from the plastic neutral axis to the top of the element where the plastic neutral axis is located (in.)
yB_{lt}	distance from the neutral axis to the bottom of the steel I-girder in the long-term composite section (in.)
yB_{nc}	distance from the neutral axis to the bottom of the steel I-girder in the noncomposite section (in.)
yB_{st}	distance from the neutral axis to the bottom of the steel I-girder in the short-term composite section (in.)
yT_{lt}	distance from the neutral axis to the top of the steel I-girder in the long-term composite section (in.)
yT_{nc}	distance from the neutral axis to the top of the steel I-girder in the noncomposite section (in.)
yT_{st}	distance from the neutral axis to the top of the steel I-girder in the short-term composite section (in.)
λ_f	slenderness ratio for the compression flange
λ_{pf}	limiting slenderness ratio for a compact flange
λ_{rf}	limiting slenderness ratio for a noncompact flange

ABSTRACT

Designing a bridge is a complex process involving numerous calculations, decisions, and design code checks. To overcome the time consuming process of hand designing a bridge, an automated design program was developed for research purposes. The program, RAMPS, is an automated finite element model construction and analysis tool recently developed by a team at Drexel University. This tool uses an Application Programming Interface between Matlab and Strand7 to automate the tedious model construction and analysis processes. Due to the automated nature of this finite element design program, it was critical that the design process was verified before it was used to carry out the proposed parametric study discussed above. The steel I-girder design component and load analysis performed by the program RAMPS was validated against AASHTO LRFD Bridge Design Specifications. To validate the program hand designs and ramps models were generated and were directly compared to check load analyses, section properties, flexural capacities, shear capacities, and the overall cross-sectional dimensions of the noncomposite girders. It was found that the RAMPS software successfully designs a girder to pass all AASHTO LRFD requirements checked, and would be able to handle any additional constraints or checks that might be necessary.

Chapter 1

INTRODUCTION

Designing a bridge is a complex process involving numerous calculations, decisions, and design code checks. Considering the number of calculations that must be performed, designers rely on bridge analysis and design software as integral tools of the design process. Bridge analysis and design programs are constantly being improved to have better calculations, easier interfaces, and faster processing speeds. It is important, however to evaluate and verify design software before it is widely used.

The purpose of this report is to validate the steel I-girder design component and load analysis performed by the program RAMPS. RAMPS is an automated finite element model construction and analysis tool recently developed by a team at Drexel University. This tool uses an Application Programming Interface (API) between Matlab and Strand7 to automate the tedious model construction and analysis processes. Using this approach, it is possible to perform large parametric studies using 3D FE models as opposed to relying exclusively on the more idealized and limited single-line girder models. Due to the automated nature of this finite element design program, it was critical that the design process was verified before it was used to carry out the proposed parametric study discussed above.

This report is limited to slab-on-girder bridges with geometric and material parameters typical to those found across the United States. Hand calculations were used to verify the designs generated by the RAMPS program. Both the hand designs and the RAMPS program follow AASHTO LRFD Specifications (2013). All discussions of articles or equations in this report refer to the AASHTO LRFD specifications, unless specified otherwise. The results from the hand calculations and RAMPS were compared to verify the design calculations for several bridge cases. The comparisons focus on moments, shears, section properties, flexural capacity and shear capacity.

Chapter 2

BRIDGE DEVELOPMENT

In an effort to validate the member-sizing software, researchers from the University of Delaware acted as independent partners to provide a “peer review” of the model design philosophy and assumptions utilized in the development of the software. A “one-to-one” approach was used in this validation effort. Several designs were conducted by hand, and key parameters of these designs were compared to the models created using the software.

Table 1: List of “One-to-one” Validation Checks

“One-to-One” Validation Checks	
• Flange Area • Web Area • Girder Depth • Girder Moment of Inertia • Girder Section Modulus • Girder Flexural Capacity	• Composite Moment of Inertia • Composite Section Modulus • Composite Section Flexural Capacity • Dead Load Computations • Live Load Computations

In this research, a case study approach was used to develop a test bed of bridges to compare. The test bed of bridges was limited to practical parameters ranges based on the focus of the NCHRP 12-103 study. This range of parameters can be found in Table 2. The test bed of bridges consisted of both simple and multiple-span bridges with composite I-girders. The values and ranges of the parameters were selected in an attempt to test the RAMPS program at the extremum of the parameters ranges that can most greatly affect a bridge design. The parameters that were chosen to be varied in the study were: number of spans, span length, roadway width, girder spacing. Deck thickness, materials properties, span to depth ratio, and barrier dimensions were held constant. This approach significantly reduced the number of bridges in the study. All bridges in the test bed had practical parameters seen in typical steel I-girder bridges. Sidewalks, and design wearing surfaces were not included in the study to further reduce the number of case studies. The reduced number of bridges examined allowed for more detailed post-processing and evaluation of results. Eight case studies were examined and can be seen in Table 3.

Table 2: Range of Applicable Parameters for NCHRP 12-103 Study

Parameters	Values
Span Length	40 ft. to 160 ft.
Bridge Width	36 ft. to 90 ft.
Girder Spacing	5 to 12 ft.
Skew Angle	0^o to 60^o
Elastic Modulus of Concrete	3000, 3500, 4000 psi
Deck Thickness	7, 8, 9, 10 in
Span to Depth Ratio	L/20, L/22, L/25, L/28, L/30
Stiffness of non-structural components (barriers and sidewalks)	Ignored
Steel Strength	50000 psi
Design Method	LRFD
Sidewalk Dimensions	10 in. high x 48 in. wide
Barrier Dimensions	27 in. high x 12 in wide
Continuity	1 Span: Simply supported >1 Span: Continuous

Table 3: Study Test Bed of Bridges

Case Number	1	2	3	4	5	6	7	8
Number of Spans	1	1	1	1	2	2	2	2
Span Length (ft.)	40	40	160	160	40	40	160	160
Number of Girders	8	18	6	12	8	18	6	12
Girder Spacing (in.)	60	60	96	96	60	60	96	96
Slab Thickness (in.)	9	9	9	9	9	9	9	9
Roadway Width (ft.)	40	90	40	90	40	90	40	90
Total Bridge Width (ft.)	42	92	42	92	42	92	42	92
Overhang Width (in.)	42	42	12	24	42	42	12	24
Span to Depth Ratio	L/20	L/20	L/20	L/20	L/20	L/20	L/20	L/20
Concrete Compressive Strength (psi)	4000	4000	4000	4000	4000	4000	4000	4000
Steel Yield Strength (psi)	50000	50000	50000	50000	50000	50000	50000	50000

Chapter 3

RAMPS SOFTWARE

RAMPS is an automated girder sizing program currently being developed by a team at Drexel University with the goal of properly develop member sizes for each bridge configuration. This software was developed to carry out research for NCHRP 12-103. To ensure the accuracy of the study, it is imperative that the sized members produced meet all requirements defined by the AASHTO LRFD Specifications. With the sample size needed to thoroughly investigate all of the potentially influential parameters of interest, automation of the member-sizing is required. The automated member sizing performed in RAMPS is intended to parallel current practice while omitting conservative practices that are not explicitly required by the AASHTO LRFD Specifications. Member sizing is based on the single-line girder method of structural analysis. Single line responses are developed using finite element approximation methods. For dead load, member actions of the single-line girder are obtained by first applying a unit distributed load and calculating the member responses of the single-line girder for that unit load. The dead load demand is then obtained by scaling those actions by the actual distributed dead load calculated for a given cross-section. For live load, member responses are obtained by stepping point loads corresponding to the axle loads of the design truck across the entire single-line girder for every combination defined by AASHTO LRFD Specifications and then calculating the member responses for each combination. Additionally, distributed loads are applied to the girder corresponding to the lane loads defined by the AASHTO LRFD Specifications. The member actions of every combination of truck and lane loading are then combined to obtain the live load envelope. These demands along with the dead load demands used to develop the total moment and shear envelopes used for sizing/capacity calculations.

Plate girder sections are dimensioned using a minimization algorithm built-in to Matlab called fmincon that according to Mathworks (2015), “attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate.” The fmincon algorithm strives to find the combination of plate girder dimensions that pass all AASHTO LRFD requirements while minimizing the area of the noncomposite cross-section. The dimensional parameters in this case are flange width, flange thickness, web thickness, and for multiple span continuous bridges, the thickness of the cover plate in the negative moment region. A minimization algorithm was utilized with the proper sizing constraints in attempt to size a cross-section that has no excess capacity but passes all AASHTO LRFD requirements. These constraints can be seen below in Tables 4 and 5. There is no rounding of cross-section dimensions so that no excess capacity is gained from this practice.

The process for member-sizing and model building is outlined in Appendix A of this report by Drexel University (2015). The process is similar between simple and multiple-span continuous bridges. The only difference is the consideration of the negative moment region. The automated member sizing software is capable of including cover plates to reinforce the negative moment region or designing a plate girder that remains constant throughout all spans. The option of a negative moment region cover-plate may be included in continuous designs, but for the purpose of this study the option was not performed.

Table 4: AASHTO LRFD Specifications Constraints member-sizing for all regions of a single span bridge and for the positive moment region of a multiple span bridge

1. Depth Criteria (2.5.2.6.3) a. $0.033L \leq D_t$ b. $0.040L \leq D$ 2. Ductility (6.10.7.3) a. $D_p \leq 0.42D_t$ 3. Web Thickness (6.7.3) a. $t_w \geq 0.3125$ 4. Section Proportions (6.10.2) a. $\frac{D}{t_w} \leq 150$ b. $\frac{b_f}{2t_f} \leq 12.0$ c. $b_f \geq \frac{D}{6}$ d. $t_f \geq 1.1t_w$ e. $0.1 \leq \frac{I_{yc}}{I_{yt}} \leq 10$	5. Service Limit (6.10.4) a. For Compact: i. $f_f \leq 0.95R_h F_{yf}$ b. For Noncompact: i. Does not control. (C6.10.4.2.2) 6. Strength Limit (6.10.4) a. For Compact: i. $\frac{2D_{cp}}{t_w} \leq 3.76\sqrt{\frac{E}{F_{yc}}}$ ii. $M_u \leq \Phi_f M_n$ iii. $V_u \leq \Phi_v V_n$ b. For Noncompact: i. $\frac{2D_{cp}}{t_w} \leq 3.76\sqrt{\frac{E}{F_{yc}}}$ ii. $f_{bu} \leq \Phi_f F_{nc}$ iii. $f_{bu} \leq \Phi_f F_{nt}$ iv. $V_u \leq \Phi_v V_n$

Table 5: Additional AASHTO LRFD Specifications constraining member-sizing for the negative moment region

5. Service Limit State (6.10.4) a. $f_f \leq 0.95R_h F_{yf}$ b. $f_c \leq F_{crw}$	6. Strength Limit State (6.10.8) a. $\frac{2D_{cp}}{t_w} \leq 3.76\sqrt{\frac{E}{F_{yc}}}$ b. $f_{bu} \leq \Phi_f F_{nc}$ c. $f_{bu} \leq \Phi_f F_{nt}$

Chapter 4

INDEPENDENT DESIGNS

Using Microsoft Excel, a design spreadsheet was developed based on the single line girder design method. Currently, the spreadsheet is only capable of handling steel girder bridge designs. The spreadsheet requires cross section dimensions, load cases, and bridge orientation information as inputs, and calculates all relevant section properties as well as the flexural and shear strength of the girder following the AASHTO LRFD Specifications. Flexural strength checks include: local buckling resistance, lateral torsional buckling resistance, and tension flange yielding resistance for both composite (positive moment region) and non-composite sections (negative moment region). Web bend-buckling resistance is also checked. The shear strength calculations only include the resistance of an unstiffened web. This was done in an attempt to parallel the model design approach of the automated modeling software, which does not include transverse or longitudinal shear stiffeners. In addition to the strength checks, all proportional limits were checked. To size the girders using the spreadsheet, calculated moment and shear capacities were checked against the factored load cases to determine to most efficient girder cross section. In this case, efficiency is determined by minimizing the cross sectional area. While designing, web thicknesses, flange widths, and flange thicknesses were sized to the nearest 1/8 in., 1/2 in., and 1/4 in., respectively.

4.1 Load Analysis

In order to efficiently design the structural components of a bridge, the loading on the bridge must be known. The dead loads, live loads, and the forces and bending moments created as a result of them were calculating in accordance with the AASHTO LRFD Bridge Design Specifications manual. Since the girder spacing is different than the roadway lane spacing, live load distribution factors were computed to determine the load supported by each girder in a given cross section. Once these loads were calculated appropriate structural analysis and design of the girder cross section could begin.

4.1.1 Dead Load

Dead loads are permanent loads that include the weight of all components of the structure and utilities attached to the structure. In the LRFD Bridge Design Specifications manual the component dead load is assumed to include all of the structure dead load except for any non-integral wearing surfaces and utility loads. For composite steel girder design the component dead load is split into two parts: the component dead load acting on the non-composite section (DC1), and the component dead load acting on the long-term composite section (DC2).

DC1 includes the dead load from the concrete deck, cross frames, and details. In the calculation of DC1, the unit weight of concrete was taken to be 0.150 kcf. Using the cross section dimensions selected for each case, DC1 was calculated, equally distributing the load to each girder in the cross section. DC2 consisted of the concrete traffic barriers and DW consisted of the wearing surface. The DC2 and DW loads were also distributed equally among each girder in a given cross section.

4.1.2 Live Load Distribution Factors

Since the spacing of the girders is not equal to the spacing of the road lanes in the cross section, only a portion of the load from each lane is applied to each interior girder. To calculate how much load each girder actually handled, distribution factors needed to be found. The live-load distribution factors for both the interior and exterior girders were determined using the equations and guidance specified in Article 4.6.2.2 of the AASHTO LRFD Bridge Design Specification manual. Different equations are given to calculate the bending moment and shear for both interior and exterior girders.

$$K_g = n(I + Ae_g^2) \qquad \text{Eqn. 1}$$

For one lane loaded:

$$DF = 0.06 + \left(\frac{S}{14}\right)^{0.4} \left(\frac{S}{L}\right)^{0.3} \left(\frac{K_g}{12.0Lt_s^3}\right)^{0.1} \qquad \text{Eqn. 2}$$

For two or more lanes loaded:

$$DF = 0.075 + \left(\frac{S}{9.5}\right)^{0.6} \left(\frac{S}{L}\right)^{0.2} \left(\frac{K_g}{12.0Lt_s^3}\right)^{0.1} \qquad \text{Eqn. 3}$$

For shear:

One lane loaded:

$$DFV = 0.36 + \frac{S}{25.0} \qquad \text{Eqn. 4}$$

Two lanes loaded:

$$DFV = 0.2 + \frac{S}{12} - (\frac{S}{35})^2 \qquad \text{Eqn. 5}$$

The live load flexural moment for exterior beams was determined by applying the lane fraction specific in Table 4.6.2.2.2d-1 of the AASHTO LRFD Specification. For one design lane loaded, the distribution factor (DF_{EXT1}) was determined by the lever rule. The lever rule is a method that involves summing moments about the first interior support to find the reaction at the exterior support by assuming that the supported component is hinged at the interior support. For two or more design lanes loaded, the following equations are used:

$$DF_{EXT2} = e * DF_{INT2} \qquad \text{Eqn. 6}$$

$$e = 0.77 + \frac{d_e}{9.1} \qquad \text{Eqn. 7}$$

For shear, the one design lane loaded distribution factor for the interior girder (DFV_{EXT1}) was also determined using the lever rule. For two or more design lanes loaded, the following equations are used:

$$DFV_{EXT2} = e * DFV_{INT2} \qquad \text{Eqn. 8}$$

$$e = 0.6 + \frac{d_e}{10} \qquad \text{Eqn. 9}$$

The AASHTO LRFD Specification states that in beam-slab bridges with diaphragms or cross-frames, the distribution factor for the exterior beam cannot be less than the value which would be obtained by assuming the cross-section deflects and rotates as a rigid unit. However, the RAMPS program currently does not calculate this, so for the purpose of comparison, it was ignored in the hand calculations and design. The RAMPS program is still being refined, and will include the distribution factor calculation assuming a rigid cross-section in the future.

To account for the probability of multiple lanes being occupied by the full HL-93 design live load, the live load force effect was determined by considering each possible combination of number of loaded lanes multiplied by a multiple presence factor. The multiple presence factors, found in Table 6, were only applied to the results from the lever rule due to the fact that the multiple presence factors were included in Eqns. 2-5 above.

Table 6: Number of Lanes Loaded and Corresponding Multiple Presence Factor

Number of Lanes Loaded	**Multiple Presence Factor**
1	1.20
2	1.00
3	0.85
>3	0.65

The dynamic allowance, IM, is a factor applied to the wheel load to account for the impact from moving vehicles. An increase of 33% for IM is applied to all limit states except the fatigue limit state.

4.1.3 Live Loads

Live load effects were generated by the finite element program STAAD (Bentley Systems, Inc., 2014) and imported into the design spreadsheet. For each given case study, each element in the model was one-tenth the total length of each span. The live load effect consisted of the design vehicular live load with the appropriate dynamic load allowances included. All live loads were considered transient loads applied to the short-term composite section.

The design vehicular live load in the LRFD specification is known as HL-93. HL-93 consists of a combination of a design truck or design tandem, and the design lane load placed within each lane. The design truck was equivalent to an AASHTO HS20 truck with the spacing between the 32 kip rear-axle loads varying between 14 and 30 ft to produce extreme force effects. The design tandem consisted of a pair of 25 kip axel loads spaced 4 ft. apart with a transverse spacing of 6 ft. The design lane load consisted of 0.64 kips/ft uniformly distributed load occupying a 10 ft lane width. The dynamic allowance is not applied to the design lane load.

For continuous spans, live load moments in regions of negative flexure between the points of permanent load contraflexure the HL-93 loading can underestimate the actual possible negative moments seen in service. For this situation, a special negative moment loading was used. In the special negative load, a second design truck is added in combination with the design lane load. The spacing between the rear-axle of the lead truck and the first axle of the following truck was set at 50 ft. The distance between the two 32 kip rear-axles of each design truck was also kept at a constant spacing of 14 ft. In addition, both the design truck and lane loads were reduced to 90 percent of their values. The live-load moments in this negative region were taken as the larger of the moments caused by either the HL-93 loading or the special negative loading. Live load shears in regions of positive and negative flexure were computed using the HL-93 loading only. However, the interior pier reactions were taken as the larger of the shears caused by either the HL-93 loading or the special negative loading.

4.1.4 Load Combinations

Load combinations are defined in the LRFD specifications to satisfy basic design objectives, which are to achieve safety, serviceability, and constructability. The combinations can be found in Table 3.4.1-1. In this report, only the Strength I, Service II, and Fatigue I load combinations were considered. Strength I is the load combination used for checking the strength of a member under normal use in the absence of wind. The Strength I load combination is 1.25 times the permanent load of a member, plus 1.5 times the load due to any non-integral wearing surfaces and utilities, plus 1.75 times the design live load. In the Service II load combination, the permanent-load load factors are all reduced to 1.0, and the live load factor is reduced to 1.3. The Fatigue I load combination is used when designing a detail or a component for an infinite fatigue life, and a load factor of 1.5 is applied to the live load fatigue stress range. These load combinations can be seen in the table below.

Table 7: Load Combinations and Corresponding Load Factors

Load Combination	**Load Factors**
Strength I	1.25DC+1.5DW+1.75(LL+IM)
Service II	1.0DC+1.0DW+1.75(LL+IM)
Fatigue I	1.5(LL+IM)

4.2 Girder Sizing

Once the load analysis was completed for each design case, both the interior and exterior girders were sized with respect to their section properties as well as the flexural, shear, and fatigue capacities. The goal of each design was to minimize the cross sectional area of the non-composite girder. In addition, for the purpose of this report, it was assumed that each girder is a composite cross-section. Therefore, the non-composite strength was not evaluated for constructability purposes. This process and relevant calculations are detailed below.

4.2.1 Proportional Limits

The AASHTO LRFD Specifications consist of many cross-section proportional limits as well as some suggested limitations. These limits detailed were developed through both experience and research and are used to improve serviceability, and economy. The cross-sectional proportional limits for a steel I-girder are specified in Article 6.10.2. Since longitudinal stiffeners were not used in this study, the girder webs were proportioned such that:

$$\frac{D}{t_w} \leq 150 \qquad \text{Eqn. 10}$$

Cross section proportional limits for flanges of steel I-sections are specified in Article 6.10.2.2. The minimum width of flanges was specified as:

$$b_f \geq \frac{D}{6} \qquad \text{Eqn. 11}$$

The minimum thicknesses of the flanges were specified as:

$$t_f \geq 1.1t_w \qquad \text{Eqn. 12}$$

Article 6.10.2.2 contained two additional proportional limits:

$$\frac{b_f}{2t_f} \leq 12.0 \qquad \text{Eqn. 13}$$

$$0.1 \leq \frac{I_{yc}}{I_{yt}} \leq 10 \qquad \text{Eqn. 14}$$

4.2.2 Effective Flange Width

The effective flange width was determined as specified in Article 4.6.2.6. According to Article 4.6.2.6, for interior girders, the effective flange width may be taken as the least of: 1) one-quarter of the effective span length, L, where L may be taken as the distance between points of permanent load contraflexure for continuous spans, 2) 12.0 times the average thickness of the slab, plus the greater of the web thickness or one-half width of the top flange of the girder, or 3) the average spacing of adjacent girders.

For exterior girders, the effective flange width was taken as one half the effective width of an interior girder, plus the least of: 1) one-eighth of the effective span length, 2) six times the average thickness of the slab, plus the greater of half the web thickness or one-quarter of the width of the tap flange, or 3) the width of the overhang.

4.2.3 Flexural Capacity

In the following sections, since RAMPS only designs homogeneous built up sections, the hybrid factor, Rh, was taken as 1.0. The web load-shedding factor, $R_{b,}$ was also taken as 1.0 because the RAMPS software forces webs to be compact, or noncompact in its optimization constraints.

4.2.3.1 Composite Section in Positive Flexure

Before calculating the composite section capacities, it was necessary to first determine the section compactness. In order to be considered compact, the yield strengths of the flanges for a section could not exceed 70.0 ksi, and the following web slenderness limit had to be met:

$$\frac{2D_{cp}}{t_w} \leq 3.76\sqrt{\frac{E}{F_{yc}}} \qquad \text{Eqn. 15}$$

If a section did not satisfy both requirements above, it was considered noncompact and was designed following the requirements of Article 6.10.7.2.

At the strength limit state, the composite sections were designed to pass the following criteria:

$$M_u \leq \Phi_f M_n \qquad \text{Eqn. 16}$$

In accordance with Article 6.4.4.2, the flexural resistance factor in the strength limit state was taken as 1.0.

The nominal flexural resistance of a compact composite section was determined as:

If $D_p \leq 0.1D_t$, then:

$$M_n = M_p \quad \text{Eqn. 17}$$

Otherwise:

$$M_n = M_p\left(1.07 - 0.7\frac{D_p}{D_t}\right) \quad \text{Eqn. 18}$$

In a continuous span, the composite section also had to satisfy:

$$M_n \leq 1.3R_hM_y \quad \text{Eqn. 19}$$

The plastic moment used in the equations above was calculated as the moment of plastic forces about the plastic neutral axis as specified in Article D6.1. Plastic forces in the steel portion of the cross-section were calculated using the strengths of the flanges and web. The strength of the reinforcing steel was ignored in this study. Plastic forces in the concrete portions of a cross-section were based on a rectangular stress block with the magnitude of the compressive stress equal to $0.85f'_c$. The equations used to determine plastic strengths of the flanges, web, and concrete can be seen below.

$$P_s = 0.85f'_cb_st_s \quad \text{Eqn. 20}$$

$$P_c = F_{yc}b_ct_c \quad \text{Eqn. 21}$$

$$P_t = F_{yt}b_tt_t \quad \text{Eqn. 22}$$

$$P_w = F_{yw}Dt_w \quad \text{Eqn. 23}$$

The position of the plastic neutral axis was determined by the equilibrium condition in which there were no axial forces. The plastic moment was then determined by:

- Calculating the element forces with the equations above and determining whether the plastic neutral axis was in the web, top flange, or concrete deck;
- Calculating the location of the plastic neutral axis within the given element;
- Calculating the plastic moment using the equations found below in Table 8.

Table 8: Calculation of $\bar{Y}$ and M_p for Sections in Positive Flexure

PNA	**Condition**	**$\bar{Y}$ and M_p**
In Web	$P_t + P_w \geq P_c + P_s$	$\bar{Y} = \left(\frac{D}{2}\right)\left[\frac{P_t - P_C - P_s}{P_w} + 1\right]$ $M_p = \frac{P_w}{2D}\left[\bar{Y}^2 + (D - \bar{Y})^2\right] + [P_s d_s + P_c d_c + P_t d_t]$
In Top Flange	$P_t + P_w + P_c \geq P_s$	$\bar{Y} = \left(\frac{t_c}{2}\right)\left[\frac{P_t + P_w - P_s}{P_c} + 1\right]$ $M_p = \left(\frac{P_c}{2t_c}\right)\left[\bar{Y}^2 + (t_c - \bar{Y})^2\right] + [P_s d_s + P_w d_w + P_t d_t]$
In Concrete Deck	$P_s \geq P_t + P_w + P_c$	$\bar{Y} = (t_s)\left[\frac{P_c + P_w + P_t}{P_s}\right]$ $M_p = \left(\frac{\bar{Y}^2 P_s}{2t_s}\right) + [P_c d_c + P_w d_w + P_t d_t]$

The yield moment, M_y, of a composite section in positive flexure was taken as the sum of moments applied separately to the steel, short-term, and long-term composite sections to cause nominal first yielding in either steel flange at the strength limit state. The calculation of yield moment was done as follows:

$$M_{AD} = S_{ST}\left(F_y - \frac{M_{D1}}{S_{NC}} - \frac{M_{D2}}{S_{LT}}\right) \qquad \text{Eqn. 24}$$

And then:

$$M_y = M_{D1} + M_{D2} + M_{AD} \qquad \text{Eqn. 25}$$

For a noncompact composite section, the compression and tension flanges were designed to satisfy:

$$f_{bu} \leq \Phi_f F_{nc} \qquad \text{Eqn. 26}$$

$$f_{bu} \leq \Phi_f F_{nt} \qquad \text{Eqn. 27}$$

The nominal flexural resistance of the compression flange in a noncompact composite section was calculated as:

$$F_{nc} = R_b R_h F_{yc} \qquad \text{Eqn. 28}$$

The nominal flexural resistance of the tension flange in a noncompact composite section was calculated as:

$$F_{nt} = R_h F_{yt} \qquad \text{Eqn. 29}$$

Both the compact and noncompact sections had to satisfy the following ductility requirement designated by Article 6.10.7.3:

$$D_p \leq 0.42 D_t \qquad \text{Eqn. 30}$$

In the service limit state, the girder was designed satisfy the following requirement under Service II loading:

$$f_f \leq 0.95 R_h F_{yf} \qquad \text{Eqn. 31}$$

4.2.3.2 Noncomposite Section in Negative Flexure

As discussed above, in the regions of negative flexure, all capacities were based on the noncomposite cross section, completely ignoring the contributions of the concrete. At the strength limit state, the compression flange must also satisfy Eqns. 26 and 27. Eqn. 28 was satisfied for both local buckling and lateral torsional buckling using the appropriate value of F_{nc} for each case. The local buckling resistance of the compression flange was calculated as:

If $\lambda_f \leq \lambda_{pf}$, then:

$$F_{nc} = R_b R_h F_{yc} \qquad \text{Eqn. 32}$$

Otherwise:

$$F_{nc} = \left[1 - \left(1 - \frac{F_{yr}}{R_h F_{yc}}\right)\left(\frac{\lambda_f - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}}\right)\right] R_b R_h F_{yc} \qquad \text{Eqn. 33}$$

Where:

$$F_{yr} = 0.7 F_{yc} \qquad \text{Eqn. 34}$$

$$\lambda_f = \frac{b_{fc}}{2t_{fc}} \qquad \text{Eqn. 35}$$

$$\lambda_{pf} = 0.38\sqrt{\frac{E}{F_{yc}}} \qquad \text{Eqn. 36}$$

$$\lambda_{rf} = 0.56\sqrt{\frac{E}{F_{yr}}} \qquad \text{Eqn. 37}$$

For unbraced lengths, the lateral torsional buckling resistance of the compression flange was calculated as:

If $L_b \leq L_p$, then:

$$F_{nc} = R_b R_h F_{yc} \qquad \text{Eqn. 38}$$

If $L_p < L_b < L_r$, then:

$$F_{nc} = C_b \left[1 - \left(1 - \frac{F_{yr}}{R_h F_{yc}}\right)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right] R_b R_h F_{yc} \leq R_b R_h F_{yc} \qquad \text{Eqn. 39}$$

If $L_b > L_r$, then:

$$F_{nc} = F_{cr} \leq R_b R_h F_{yc} \qquad \text{Eqn. 40}$$

Where:

$$L_p = 1.0 r_t \sqrt{\frac{E}{F_{yc}}} \qquad \text{Eqn. 41}$$

$$L_r = \pi r_t \sqrt{\frac{E}{F_{yr}}} \qquad \text{Eqn. 42}$$

$$r_t = \frac{b_{fc}}{\sqrt{12\left(1 + \frac{1}{3}\frac{D_c t_w}{b_{fc} t_{fc}}\right)}} \qquad \text{Eqn. 43}$$

$$F_{cr} = \frac{C_b R_b \pi^2 E}{\left(\frac{L_b}{r_t}\right)^2} \qquad \text{Eqn. 44}$$

The nominal resistance in the tension flange was calculated as:

$$F_{nt} = R_h F_{yt} \qquad \text{Eqn. 45}$$

The moment gradient modifier, C_b, was taken as 1.0 for this study.

In the service limit state, both steel flanges were designed satisfy the following requirement under Service II loading:

$$f_f \leq 0.80 R_h F_{yf} \qquad \text{Eqn. 48}$$

And:

$$f_c \leq F_{crw} \qquad \text{Eqn. 47}$$

4.2.3.3 Web Bend-Buckling Resistance

In webs without longitudinal stiffeners, the web bend-buckling capacity must be checked. The web bend-buckling resistance was calculated in both the positive and negative bending moment regions. The nominal bend-buckling resistance was calculated as:

$$F_{crw} = \frac{0.9Ek}{\left(\frac{D}{t_w}\right)^2} \qquad \text{Eqn. 48}$$

This bend-buckling resistance could not exceed the smaller of $R_h F_{yc}$ and $F_{yw}/0.7$.

Where:

$$k = \frac{9}{(D_c/D)^2} \qquad \text{Eqn. 49}$$

4.2.4 Shear Capacity

The RAMPS program do not use any longitudinal stiffeners, therefore, the shear capacity was calculated with respect to an unstiffened web. For a given girder the web was designed to satisfy:

$$V_u \leq \Phi_v V_n \qquad \text{Eqn. 50}$$

In accordance with Article 6.4.4.2, the shear resistance factor in the strength limit state was taken as 1.0. The nominal shear resistance of an unstiffened web was calculated as:

$$V_n = V_{cr} = CV_p \qquad \text{Eqn. 51}$$

In which:

$$V_p = 0.58F_{yw}Dt_w \qquad \text{Eqn. 52}$$

The ratio was calculated as specified below:

If $\frac{D}{t_w} \leq 1.12\sqrt{\frac{Ek}{F_{yw}}}$, then:

$$C = 1.0 \qquad \text{Eqn. 53}$$

If $1.12\sqrt{\frac{Ek}{F_{yw}}} \leq \frac{D}{t_w} \leq 1.40\sqrt{\frac{Ek}{F_{yw}}}$, then:

$$C = \frac{1.12}{D/t_w}\sqrt{\frac{Ek}{F_{yw}}} \qquad \text{Eqn. 54}$$

If $\frac{D}{t_w} > 1.40\sqrt{\frac{Ek}{F_{yw}}}$, then:

$$C = \frac{1.57}{\left(\frac{D}{t_w}\right)^2}\left(\frac{Ek}{F_{yw}}\right) \qquad \text{Eqn. 55}$$

Where:

$k = 5.0$

Chapter 5

RESULTS

The complete set of case studies of the steel I-girder bridges were analyzed using both the RAMPS software, and hand calculations. As stated above, hand calculations were performed utilizing STAAD and a generated design spreadsheet. This section focuses on the comparisons of moments, shears, section properties, flexural strength, and shear strength. The comparisons were used to identify any numerical discrepancies and the possible underlying causes or assumptions leading to these differences. The following results shown summarize the numerous load analyses and design calculations performed in order to verify the RAMPS Program.

The comparisons of the unfactored and undistributed live load moment and shear envelopes computed by RAMPS and STAAD are shown in Figures 5-1 through 5-8. The live load envelopes are compared because they involved the use of a finite element numerical evaluation of many stepped loads over a given span. The dead load calculations are based off of the calculations of a distributed load over the entire span, which is relatively simple. Figures 5-1 and 5-2 show the comparison of live load moments and shears for Cases 1 and 2. Figures 5-3 and 5-4 show the comparison of live load moments and shears for Cases 3 and 4. Figures 5-5 and 5-6 show the comparison of live load moments and shears for Cases 5 and 6. Figures 5-7 and 5-8 show the comparison of live load moments and shears for Cases 7 and 8. Since a single line girder analysis was used, cases that had the same number of spans and span lengths had the same unfactored and undistributed live loading. The figures show good agreement at all locations along the span. The actual numerical differences at the points of interest can be found in Tables 9-24. Many of the differences can be attributed to the fact that the element sizes were different in the finite element analyses performed by RAMPS and STAAD. In RAMPS the elements were all 1 ft. long; in STAAD they were one-tenth of the span length. This may also be the reason why the calculations have greater percent differences with an increase in span length. The difference in RAMPS and STAAD element lengths increased with an increase in span length.

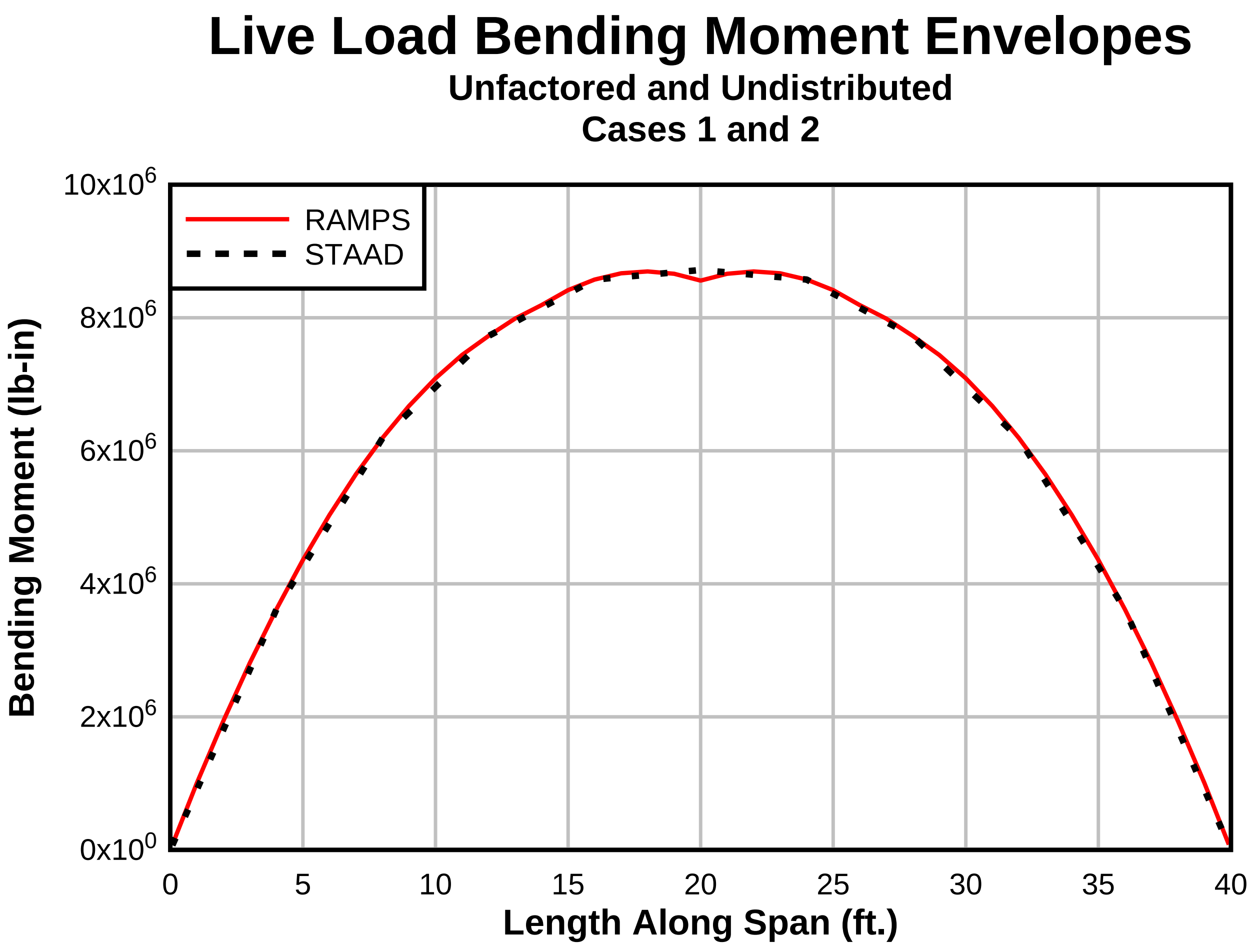

Figure 1: Unfactored and Undistributed Live Load Bending Moment Envelope for Cases 1 and 2

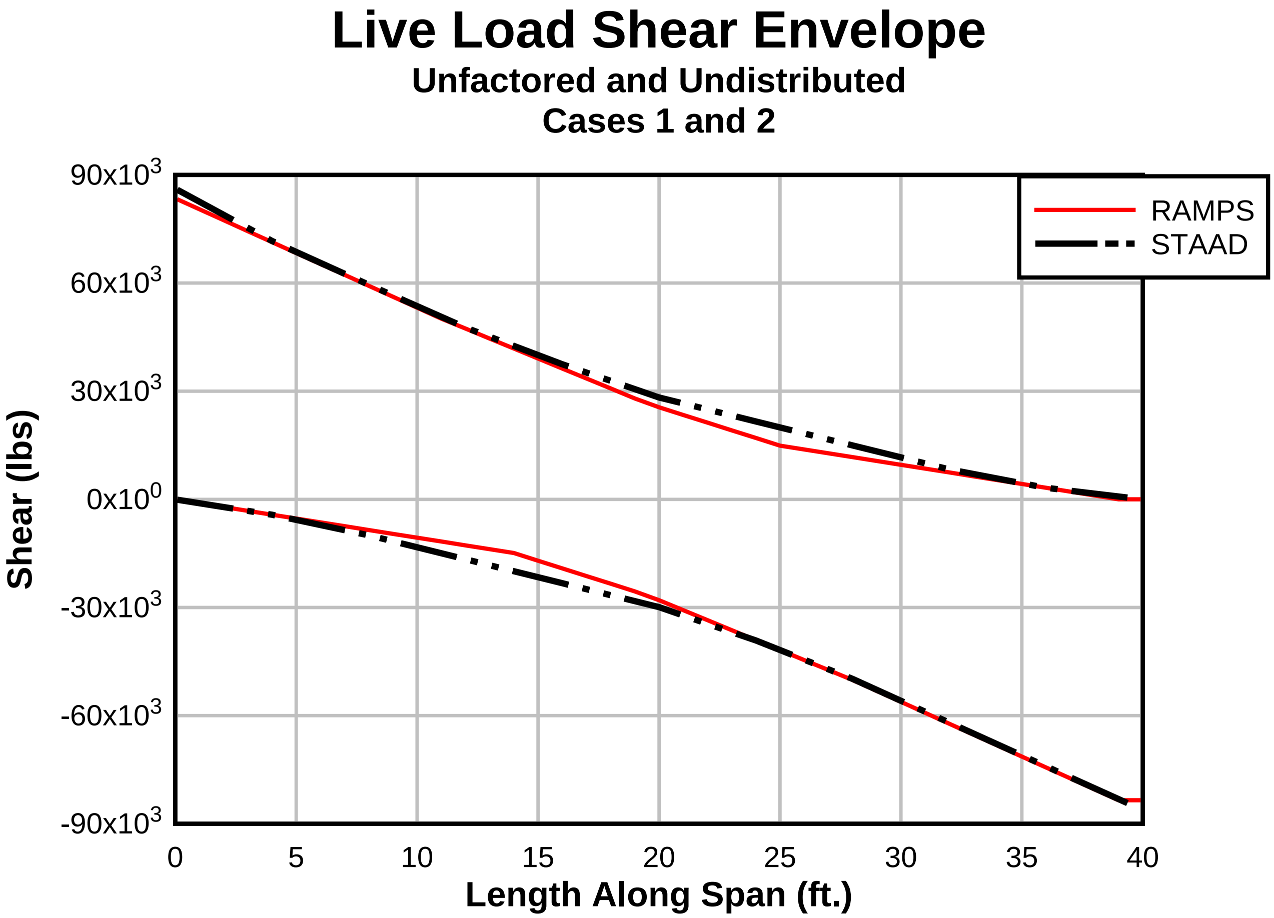

Figure 2: Unfactored and Undistributed Live Load Shear Envelope for Cases 1 and 2

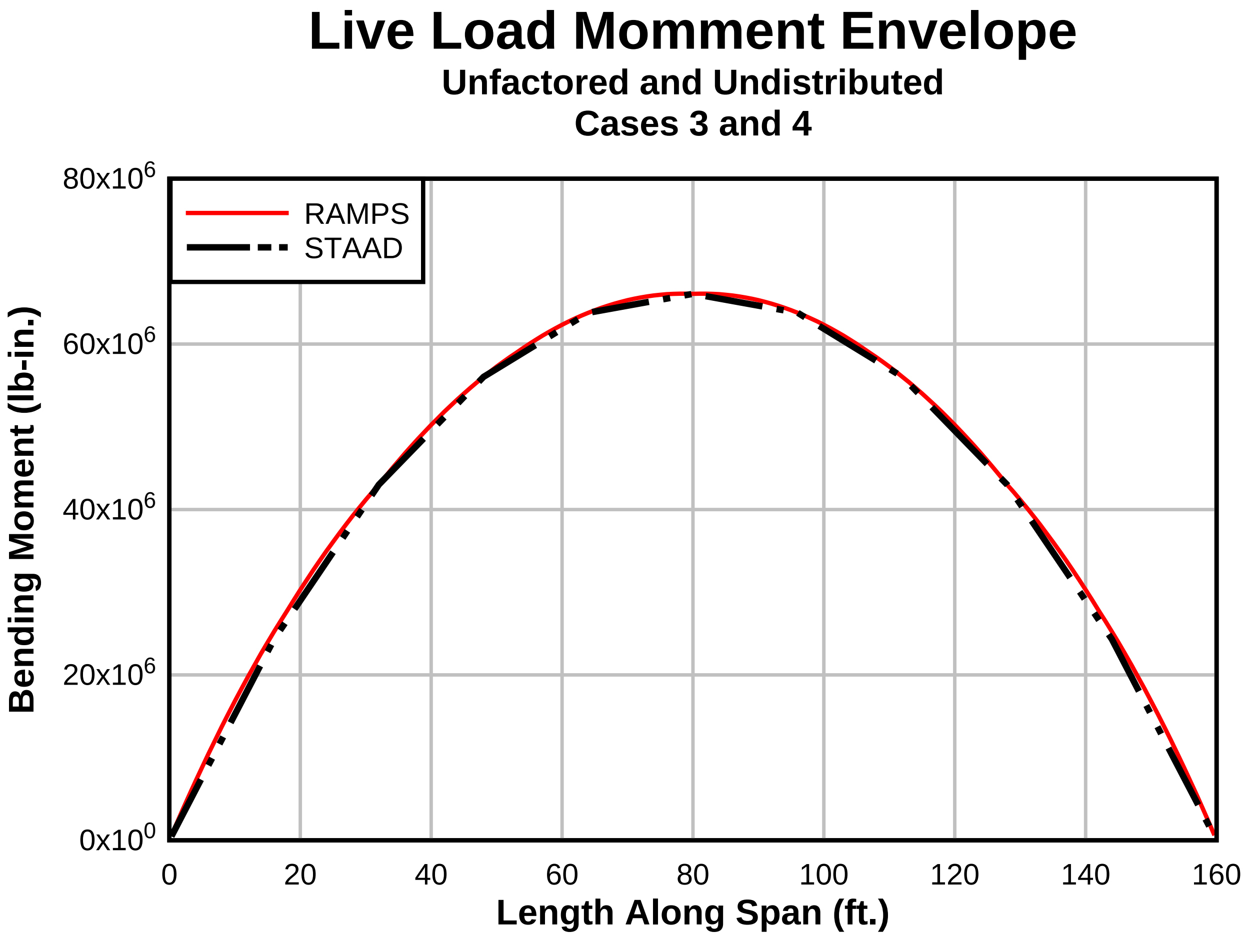

Figure 3: Unfactored and Undistributed Live Load Bending Moment Envelope for Cases 3 and 4

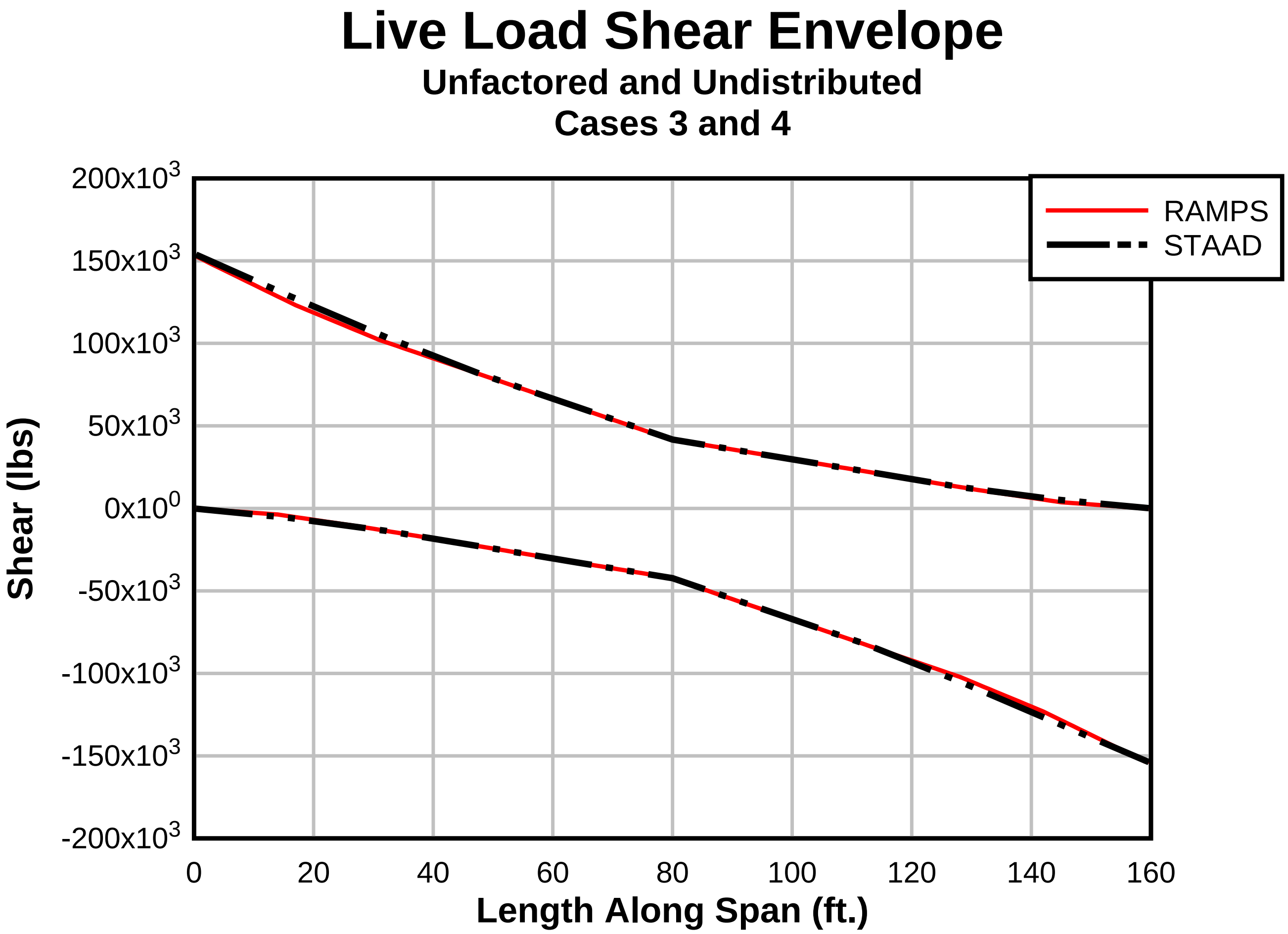

Figure 4: Unfactored and Undistributed Live Load Shear Envelope for Cases 3 and 4

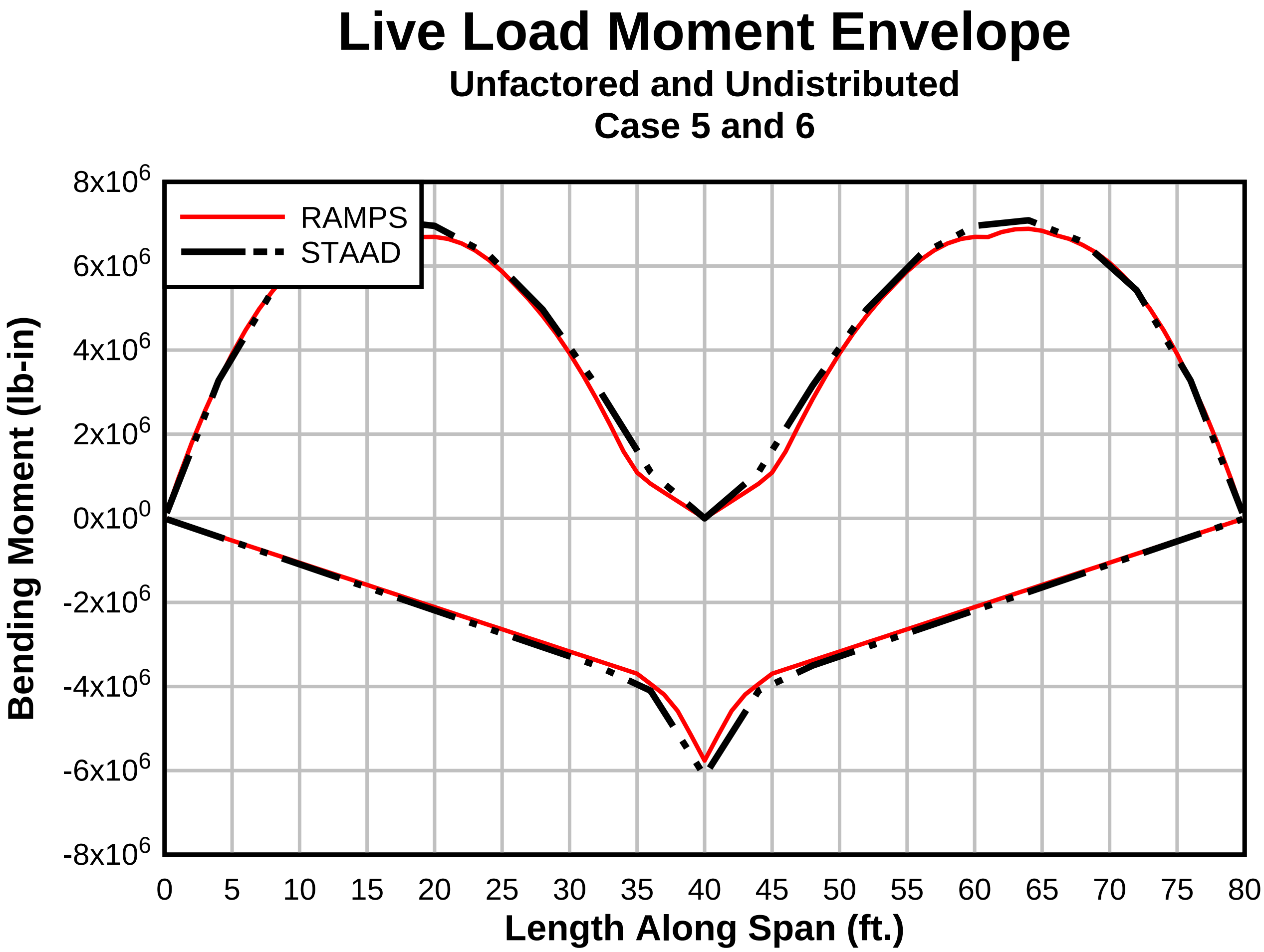

Figure 5: Unfactored and Undistributed Live Load Bending Moment Envelope for Cases 5 and 6

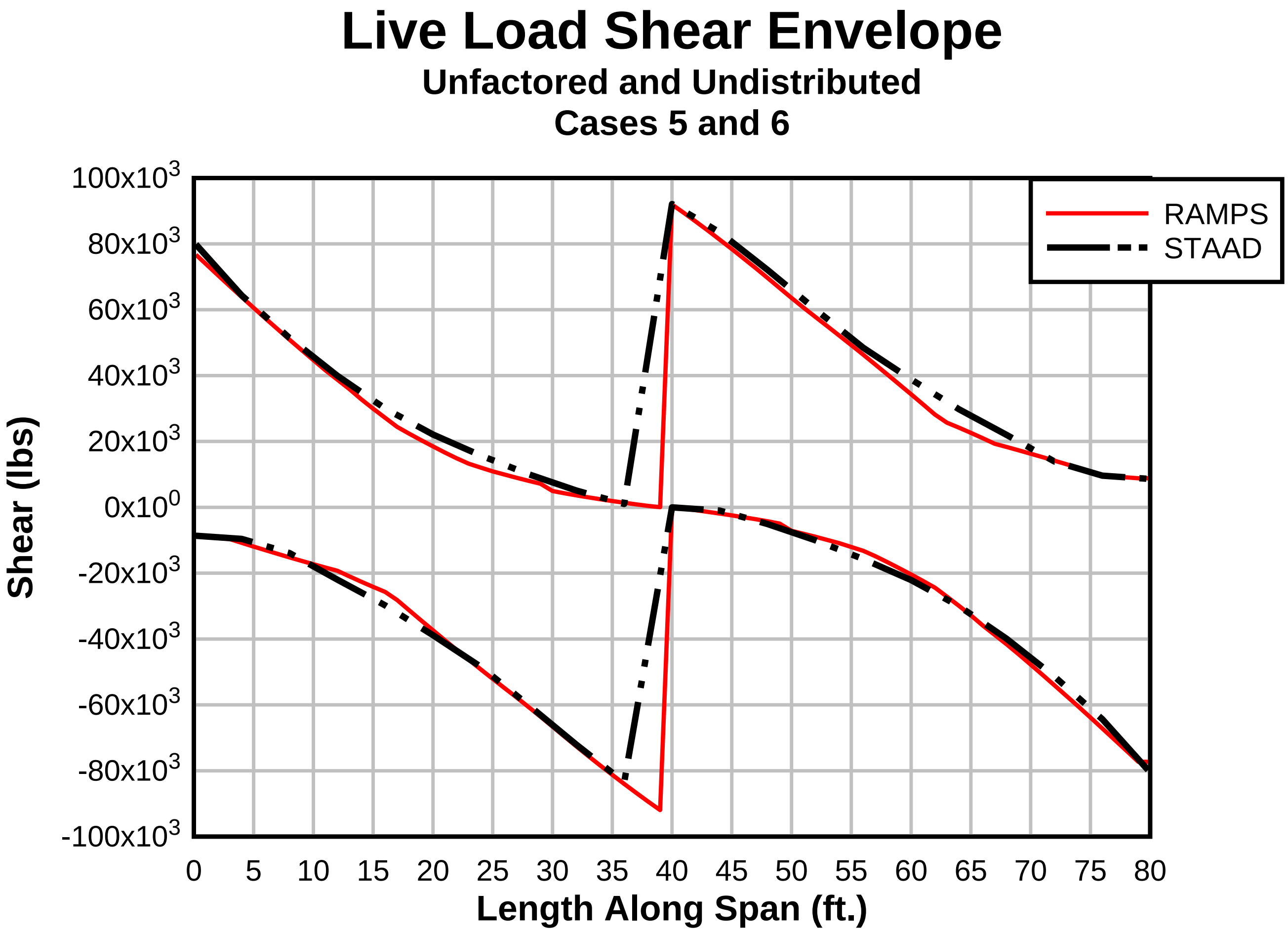

Figure 6: Unfactored and Undistributed Live Load Shear Envelope for Cases 5 and 6

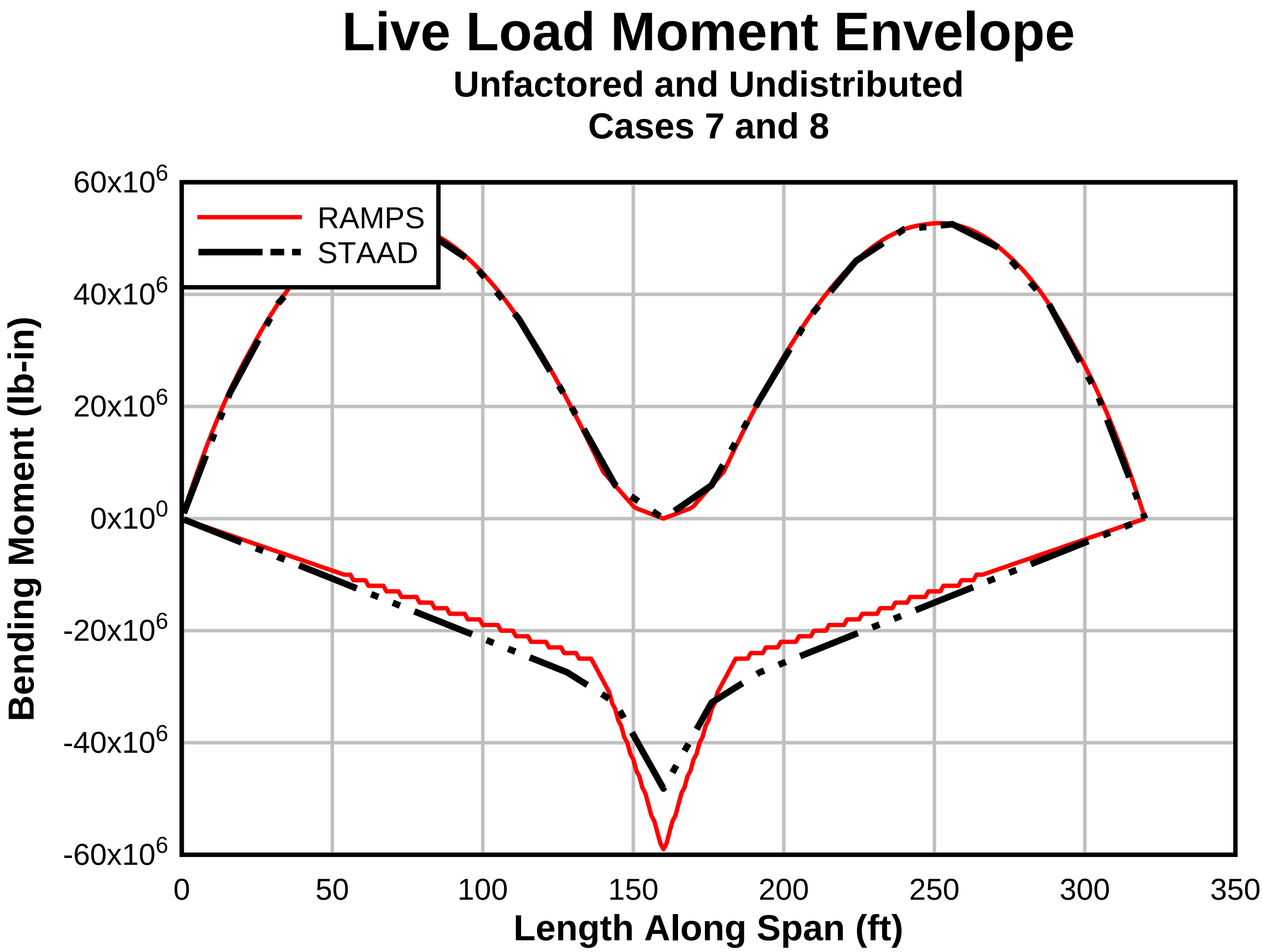

Figure 7: Unfactored and Undistributed Live Load Bending Moment Envelope for Cases 7 and 8

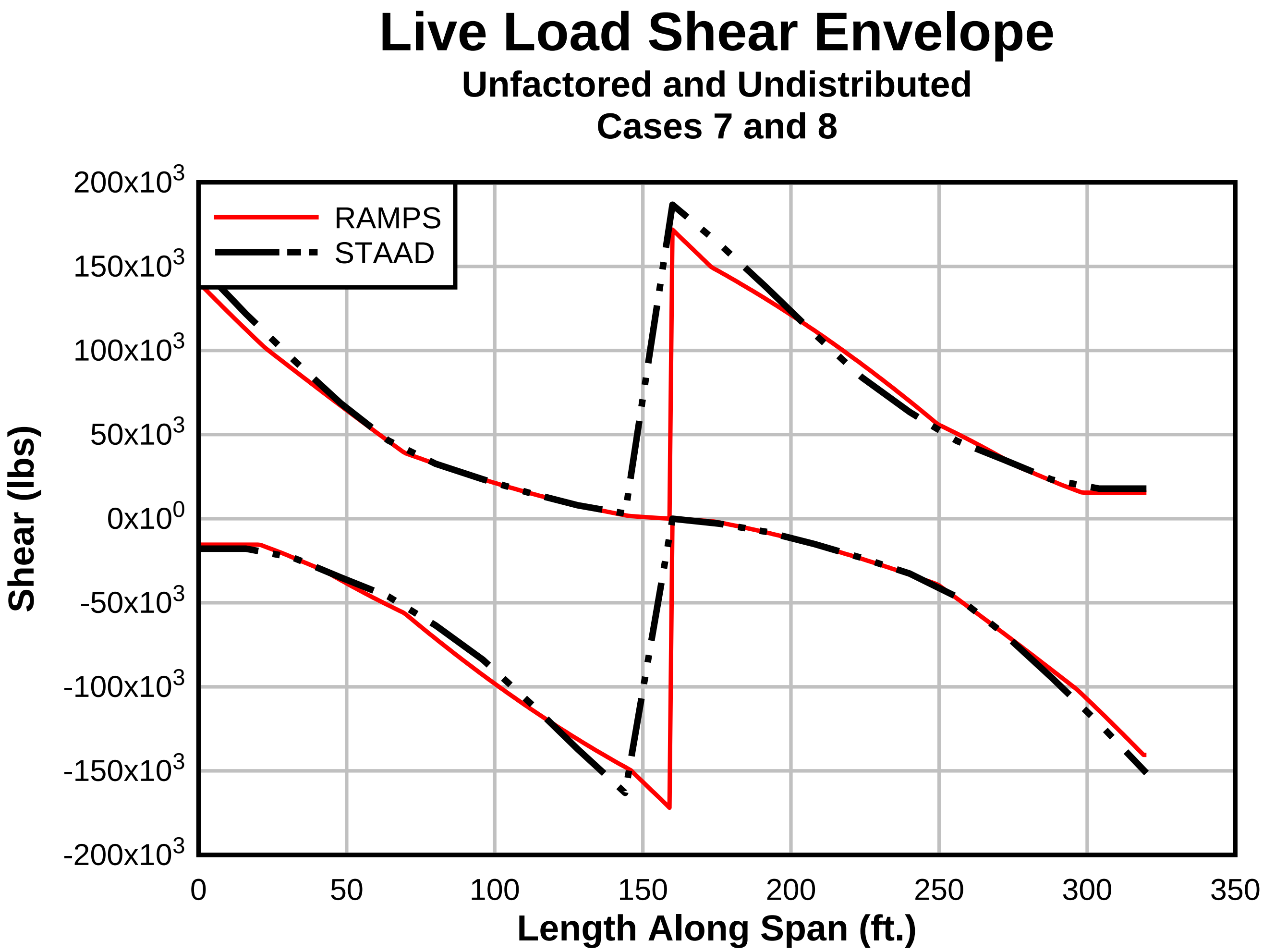

Figure 8: Unfactored and Undistributed Live Load Shear Envelope for Cases 7 and 8

Tables 9-16 below show all one-to-one comparisons for the bridge case studies performed. The results compared are the hand calculations done with the design spreadsheet and those performed by the RAMPS software. All designs seen below pass all checked LRFD constraints. When comparing the results, it can be seen that the RAMPS software has the ability to design a more efficient cross section by not rounding, but was not able to in Cases 1, 2, 6, 7, and 8. The reason for this is that the optimization function may be getting stuck in local minimum, while passing all constraints. This may be why in some of the cases a seemingly large dimension was chosen.

All subsequent section property calculations, flexural capacities, and shear strengths were dependent on the girder dimensions, so it was very unlikely that if the design dimensions were different that the section property calculations would be close. However, what was found that for the governing flexural or shear capacity in a given case, the calculated capacities had a small percent difference. For the single span bridges this coincided with the composite positive moment flexural capacity. For the two-span continuous, this coincided with the negative noncomposite flexural capacity.

Table 9: Case 1 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Converted Hand Value	RAMPS Value	Percent Difference
D (in.)	23.000	23.000	0.00	23.000	23.000	0.00
b_f (in.)	4.000	6.000	-40.00	4.000	8.467	-71.66
t_f (in.)	0.500	0.500	0.00	0.500	0.500	0.00
t_w (in.)	0.375	0.313	18.18	0.375	0.313	18.18
A (in^2)	12.625	14.487	-13.74	12.625	17.583	-32.82
Ix (in^4)	9.326E+02	1.145E+03	-20.48	9.326E+02	1.486E+03	-45.77
Iyc (in^4)	2.667E+00	9.000E+00	-108.57	2.667E+00	2.529E+01	-161.85
Iyt (in^4)	2.667E+00	9.000E+00	-108.57	2.667E+00	2.529E+01	-161.85
Ist (in^4)	4.279E+03	4.599E+03	-7.22	4.448E+03	5.598E+03	-22.90
Ilt (in^4)	3.281E+03	3.555E+03	-8.03	3.452E+03	4.360E+03	-23.24
yTnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBst (in.)	25.888	25.791	0.38	26.264	25.815	1.72
yTst (in.)	1.888	1.791	5.29	2.264	1.815	22.02
yBlt (in.)	22.548	22.382	0.74	23.223	22.423	3.50
yTly (in.)	1.452	1.618	-10.87	0.777	1.577	-67.97
STnc (in^3)	7.771E+01	9.545E+01	-20.48	7.771E+01	1.238E+02	-45.77
SBnc (in^3)	7.771E+01	9.545E+01	-20.48	7.771E+01	1.238E+02	-45.77
STst (in^3)	2.266E+03	2.568E+03	-12.50	1.964E+03	3.084E+03	-44.37
SBst (in^3)	1.653E+02	1.783E+02	-7.60	1.693E+02	2.169E+02	-24.60
STlt (in^3)	2.260E+03	2.197E+03	2.85	4.443E+03	2.765E+03	46.56
SBlt (in^3)	1.455E+02	1.589E+02	-8.77	1.486E+02	1.944E+02	-26.69
Mn_pos (lb-in)	1.228E+07	1.278E+07	-4.00	1.244E+07	1.519E+07	-19.86
Fn_neg (ln-in)	3.720E+00	0.000E+00	0.00	3.720E+03	0.000E+00	0.00
Vn (lbs)	2.460E+05	1.708E+05	36.07	2.460E+05	1.708E+05	36.07
Mp (lb-in)	1.228E+07	1.278E+07	-4.00	1.244E+07	1.519E+07	-19.86
DF	0.430	0.435	-1.11	0.660	0.660	0.00
DFV	0.596	0.596	0.00	0.660	0.660	0.00

Table 9: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	49.219	49.219	0.00	49.219	49.219	0.00
Dlstringer (lbs/in)	3.795	3.964	-4.36	3.795	4.705	-21.43
Dldiaphragm (lbs/in)	0.228	0.228	0.00	0.228	0.228	0.00
Dlparapet (lbs/in)	7.031	7.031	0.00	7.031	7.031	0.00
wDL (lbs/in)	53.242	53.411	-0.32	53.242	54.153	-1.70
wSDL (lbs/in)	7.031	7.031	0.00	7.031	7.031	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	1.533E+06	1.538E+06	-0.32	1.533E+06	1.560E+06	-1.70
MDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDL_pos (lb-in)	2.025E+05	2.025E+05	0.00	2.025E+05	2.025E+05	0.00
MSDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.447E+04	1.451E+04	-0.28	1.278E+04	1.468E+04	-13.88
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	8.718E+06	8.559E+06	1.84	8.718E+06	8.559E+06	1.84
MLL_neg1 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_1 (lbs)	8.622E+04	8.351E+04	3.19	8.622E+04	8.351E+04	3.19
MLL_pos2 (lb-in)	3.747E+06	3.720E+06	0.73	5.754E+06	5.649E+06	1.84
MLL_neg2 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_2(lbs)	5.141E+04	4.979E+04	3.19	5.141E+04	5.512E+04	-6.96
M_pos (lb-in)	8.727E+06	8.685E+06	0.48	1.224E+07	1.209E+07	1.24
M_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
V (lbs)	1.080E+05	1.016E+05	6.11	1.177E+05	1.148E+05	2.46

Table 10: Case 2 Results Comparison

Parameter	Interior			Exterior		
	Converted Hand Value	RAMPS Value	Percent Difference	Converted Hand Value	RAMPS Value	Percent Difference
D (in.)	23.000	23.000	0.00	23.000	23.000	0.00
b_f (in.)	4.000	6.000	-40.00	4.000	8.204	-68.89
t_f (in.)	0.500	0.500	0.00	0.500	0.500	0.00
t_w (in.)	0.375	0.313	18.18	0.375	0.313	18.18
A (in^2)	12.625	13.188	-4.36	12.625	15.391	-19.75
Ix (in^4)	9.326E+02	1.145E+03	-20.48	9.326E+02	1.450E+03	-43.41
Iyc (in^4)	2.667E+00	9.000E+00	-108.57	2.667E+00	2.300E+01	-158.45
Iyt (in^4)	2.667E+00	9.000E+00	-108.57	2.667E+00	2.300E+01	-158.45
Ist (in^4)	4.279E+03	4.599E+03	-7.22	4.448E+03	5.511E+03	-21.36
Ilt (in^4)	3.281E+03	3.555E+03	-8.03	3.452E+03	4.294E+03	-21.76
yTnc (in.)	12.00	12.00	0.00	12.00	12.00	0.00
yBnc (in.)	12.00	12.00	0.00	12.00	12.00	0.00
yBst (in.)	25.89	25.79	0.38	26.26	25.85	1.58
yTst (in.)	1.89	1.79	5.29	2.26	1.85	19.98
yBlt (in.)	22.55	22.38	0.74	23.22	22.49	3.22
yTly (in.)	1.45	1.62	-10.87	0.78	1.51	-64.22
STnc (in^3)	7.771E+01	9.545E+01	-20.48	7.771E+01	1.208E+02	-43.41
SBnc (in^3)	7.771E+01	9.545E+01	-20.48	7.771E+01	1.208E+02	-43.41
STst (in^3)	2.266E+03	2.568E+03	-12.50	1.964E+03	2.974E+03	-40.90
SBst (in^3)	1.653E+02	1.783E+02	-7.60	1.693E+02	2.132E+02	-22.92
STlt (in^3)	2.260E+03	2.197E+03	2.85	4.443E+03	2.840E+03	44.00
SBlt (in^3)	1.455E+02	1.589E+02	-8.77	1.486E+02	1.910E+02	-24.93
Mn_pos (lb-in)	1.228E+07	1.278E+07	-4.00	1.244E+07	1.495E+07	-18.32
Fn_neg (ln-in)	3.720E+00	0.000E+00	0.00	3.720E+00	0.000E+00	0.00
Vn (lbs)	2.460E+05	1.708E+05	36.07	2.460E+05	1.708E+05	36.07
Mp (lb-in)	1.228E+07	1.278E+07	-4.00	1.244E+07	1.495E+07	-18.32
DF	0.43	0.43	-1.06	0.66	0.66	0.00
DFV	0.60	0.60	0.00	0.66	0.66	0.00

Table 10: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	47.917	47.917	0.00	47.917	47.917	0.00
Dlstringer (lbs/in)	3.795	3.964	-4.36	3.795	4.626	-19.75
Dldiaphragm (lbs/in)	0.228	0.228	0.00	0.228	0.228	0.00
Dlparapet (lbs/in)	3.125	3.125	0.00	3.125	3.125	0.00
wDL (lbs/in)	51.940	52.109	-0.32	55.065	52.771	4.25
wSDL (lbs/in)	3.125	3.125	0.00	3.125	3.125	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	1.496E+06	1.501E+06	-0.32	1.496E+06	1.520E+06	-1.59
MDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDL_pos (lb-in)	9.000E+04	9.000E+04	0.00	9.000E+04	9.000E+04	0.00
MSDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.322E+04	1.326E+04	-0.31	1.247E+04	1.342E+04	-7.34
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	8.718E+06	8.559E+06	1.84	8.718E+06	8.559E+06	1.84
MLL_neg1 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_1 (lbs)	8.622E+04	8.351E+04	3.19	8.622E+04	8.351E+04	3.19
MLL_pos2 (lb-in)	3.749E+06	3.720E+06	0.78	1.007E+07	5.649E+06	56.24
MLL_neg2 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_2(lbs)	5.141E+04	4.979E+04	3.19	9.958E+04	5.512E+04	57.49
M_pos (lb-in)	8.543E+06	8.498E+06	0.53	1.205E+07	1.190E+07	1.28
M_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
V (lbs)	1.065E+05	1.037E+05	2.64	1.161E+05	1.132E+05	2.51

Table 11: Case 3 Results Comparison

Parameter	Interior			Exterior		
	Converted Hand Value	RAMPS Value	Percent Difference	Converted Hand Value	RAMPS Value	Percent Difference
D (in.)	94.500	94.612	-0.12	94.500	94.612	-0.12
b_f (in.)	16.000	16.000	0.00	16.000	16.000	0.00
t_f (in.)	0.750	0.694	7.78	0.750	0.694	7.78
t_w (in.)	0.750	0.631	17.27	0.750	0.631	17.27
A (in^2)	94.875	81.879	14.71	94.875	81.879	14.71
Ix (in^4)	1.072E+05	9.493E+04	12.12	1.072E+05	9.493E+04	12.12
Iyc (in^4)	2.560E+02	2.368E+02	7.78	2.560E+02	2.368E+02	7.78
Iyt (in^4)	2.560E+02	2.368E+02	7.78	2.560E+02	2.368E+02	7.78
Ist (in^4)	2.468E+05	2.237E+05	9.79	2.160E+05	1.971E+05	9.17
Ilt (in^4)	1.791E+05	1.638E+05	8.88	1.572E+05	1.435E+05	9.12
yTnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBst (in.)	75.876	77.790	-2.49	69.754	71.651	-2.68
yTst (in.)	20.124	18.210	9.99	26.246	24.349	7.50
yBlt (in.)	62.383	63.972	-2.51	58.019	59.268	-2.13
yTly (in.)	33.617	32.028	4.84	37.981	36.732	3.34
STnc (in^3)	2.233E+03	1.978E+03	12.12	2.233E+03	1.978E+03	12.12
SBnc (in^3)	2.233E+03	1.978E+03	12.12	2.233E+03	1.978E+03	12.12
STst (in^3)	1.226E+04	1.229E+04	-0.19	8.229E+03	8.093E+03	1.67
SBst (in^3)	3.252E+03	2.876E+03	12.28	3.096E+03	2.750E+03	11.84
STlt (in^3)	5.327E+03	5.115E+03	4.05	4.140E+03	3.907E+03	5.78
SBlt (in^3)	2.870E+03	2.561E+03	11.39	2.710E+03	2.422E+03	11.24
Mn_pos (lb-in)	2.260E+08	2.093E+08	7.65	1.833E+08	1.708E+08	7.07
Fn_neg (ln-in)	2.054E+01	0.000E+00	0.00	2.054E+01	0.000E+00	0.00
Vn (lbs)	5.895E+05	3.500E+05	50.98	5.895E+05	3.500E+05	50.98
Mp (lb-in)	2.376E+08	2.093E+08	12.65	2.148E+08	1.931E+08	10.61
DF	0.608	0.602	1.05	0.450	0.463	-2.91
DFV	0.814	0.814	0.00	0.450	0.489	-8.24

Table 11: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	65.625	65.625	0.00	65.625	65.625	0.00
Dlstringer (lbs/in)	28.517	24.611	14.71	28.517	24.611	14.71
Dldiaphragm (lbs/in)	0.121	0.122	-0.78	0.121	0.122	-0.78
Dlparapet (lbs/in)	9.375	9.375	0.00	9.375	9.375	0.00
wDL (lbs/in)	94.263	0.000	0.00	94.263	90.358	4.23
wSDL (lbs/in)	9.375	9.375	0.00	9.375	9.375	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	4.344E+07	4.164E+07	4.23	4.344E+07	4.164E+07	4.23
MDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDL_pos (lb-in)	4.320E+06	4.320E+06	0.00	4.320E+06	4.320E+06	0.00
MSDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	9.049E+04	9.574E+04	-5.64	9.049E+04	9.574E+04	-5.64
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	6.607E+07	6.607E+07	0.00	6.607E+07	6.607E+07	0.00
MLL_neg1 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_1 (lbs)	1.543E+05	1.534E+05	0.60	1.543E+05	1.534E+05	0.60
MLL_pos2 (lb-in)	4.017E+07	3.976E+07	1.04	2.973E+07	3.061E+07	-2.92
MLL_neg2 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_2(lbs)	1.257E+05	1.250E+05	0.60	6.946E+04	7.108E+04	-2.32
M_pos (lb-in)	1.300E+08	1.270E+08	2.32	1.117E+08	1.110E+08	0.64
M_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
V (lbs)	3.443E+05	2.812E+05	20.18	2.459E+05	2.441E+05	0.75

Table 12: Case 4 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
D (in.)	94.500	94.612	-0.12	94.500	89.846	5.05
b_f (in.)	16.000	16.000	0.00	16.000	16.008	-0.05
t_f (in.)	0.750	0.694	7.78	0.750	3.077	-121.61
t_w (in.)	0.750	0.631	17.27	0.750	0.602	21.95
A (in^2)	94.875	81.879	14.71	94.875	152.572	-46.63
Ix (in^4)	1.072E+05	9.493E+04	12.12	1.072E+05	2.491E+05	-79.67
Iyc (in^4)	2.560E+02	2.368E+02	7.78	2.560E+02	1.052E+03	-121.71
Iyt (in^4)	2.560E+02	2.368E+02	7.78	2.560E+02	1.052E+03	-121.71
Ist (in^4)	2.468E+05	2.237E+05	9.79	2.160E+05	3.950E+05	-58.59
Ilt (in^4)	1.791E+05	1.638E+05	8.88	1.572E+05	3.122E+05	-66.03
yTnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBst (in.)	75.876	77.790	-2.49	69.754	66.141	5.32
yTst (in.)	20.124	18.210	9.99	26.246	29.859	-12.88
yBlt (in.)	62.383	63.972	-2.51	58.019	55.857	3.80
yTly (in.)	33.617	32.028	4.84	37.981	40.143	-5.54
STnc (in^3)	2.233E+03	1.978E+03	12.12	2.233E+03	5.190E+03	-79.67
SBnc (in^3)	2.233E+03	1.978E+03	12.12	2.233E+03	5.190E+03	-79.67
STst (in^3)	1.226E+04	1.229E+04	-0.19	8.229E+03	1.323E+04	-46.59
SBst (in^3)	3.252E+03	2.876E+03	12.28	3.096E+03	5.971E+03	-63.41
STlt (in^3)	5.327E+03	5.115E+03	4.05	4.140E+03	7.778E+03	-61.05
SBlt (in^3)	2.870E+03	2.561E+03	11.39	2.710E+03	5.590E+03	-69.39
Mn_pos (lb-in)	2.260E+08	2.093E+08	7.65	1.833E+08	3.409E+08	-60.14
Fn_neg (ln-in)	0.000+00	0.000E+00	0.00	2.054E+01	0.000+00	0.00
Vn (lbs)	5.895E+05	3.500E+05	50.98	5.895E+05	3.198E+05	59.30
Mp (lb-in)	2.376E+08	2.093E+08	12.65	2.148E+08	3.649E+08	-51.79
DF	0.608	0.602	1.05	0.600	0.600	0.00
DFV	0.814	0.814	0.00	0.600	0.600	0.00

Table 12: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	71.875	71.875	0.00	71.875	71.875	0.00
Dlstringer (lbs/in)	28.517	24.611	14.71	28.517	45.860	-46.63
Dldiaphragm (lbs/in)	0.121	0.122	-0.78	0.121	0.122	-0.78
Dlparapet (lbs/in)	4.688	4.688	0.00	4.688	4.688	0.00
wDL (lbs/in)	100.513	96.608	3.96	100.513	117.856	-15.88
wSDL (lbs/in)	4.688	4.688	0.00	4.688	4.688	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	4.632E+07	4.452E+07	3.96	4.632E+07	5.431E+07	-15.88
MDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDL_pos (lb-in)	2.160E+06	2.160E+06	0.00	2.160E+06	2.160E+06	0.00
MSDL_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	9.649E+04	9.724E+04	-0.78	9.649E+04	1.176E+05	-19.75
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	6.607E+07	6.607E+07	0.00	6.607E+07	6.607E+07	0.00
MLL_neg1 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_1 (lbs)	1.414E+05	1.534E+05	-8.18	1.414E+05	1.534E+05	-8.18
MLL_pos2 (lb-in)	4.017E+07	3.976E+07	1.04	6.938E+07	3.964E+07	54.54
MLL_neg2 (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VLL_2(lbs)	1.257E+05	1.250E+05	0.60	1.621E+05	9.206E+04	55.10
M_pos (lb-in)	1.309E+08	1.279E+08	2.30	1.300E+08	1.400E+08	-7.40
M_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
V (lbs)	3.462E+05	3.645E+05	-5.15	2.883E+05	3.082E+05	-6.65

Table 13: Case 5 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
D (in.)	22.500	22.770	-1.19	22.500	21.671	3.75
b_f (in.)	10.000	11.254	-11.80	12.000	9.590	22.32
t_f (in.)	0.750	0.615	19.80	0.750	1.164	-43.28
t_w (in.)	0.313	0.314	-0.51	0.313	0.318	-1.80
A (in^2)	22.031	20.992	4.83	25.031	29.226	-15.46
Ix (in^4)	2.324E+03	2.202E+03	5.43	2.730E+03	3.184E+03	-15.34
Iyc (in^4)	6.250E+01	7.304E+01	-15.55	1.080E+02	8.558E+01	23.17
Iyt (in^4)	6.250E+01	7.304E+01	-15.55	1.080E+02	8.558E+01	23.17
Ist (in^4)	7.293E+03	7.008E+03	3.99	8.473E+03	9.566E+03	-12.12
Ilt (in^4)	5.498E+03	5.301E+03	3.64	6.438E+03	7.175E+03	-10.82
yTnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBst (in.)	24.423	24.569	-0.60	24.588	24.107	1.98
yTst (in.)	0.423	0.569	-29.53	-0.588	0.107	289.16
yBlt (in.)	20.314	20.513	-0.98	20.539	19.901	3.16
yTly (in.)	3.686	3.487	5.55	3.461	4.099	-16.90
STnc (in^3)	1.937E+02	1.835E+02	5.43	2.275E+02	2.653E+02	-15.34
SBnc (in^3)	1.937E+02	1.835E+02	5.43	2.275E+02	2.653E+02	-15.34
STst (in^3)	1.725E+04	1.231E+04	33.42	1.440E+04	8.922E+04	-144.40
SBst (in^3)	2.986E+02	2.852E+02	4.58	3.446E+02	3.968E+02	-14.09
STlt (in^3)	1.492E+03	1.520E+03	-1.92	1.860E+03	1.750E+03	6.11
SBlt (in^3)	2.706E+02	2.584E+02	4.61	3.135E+02	3.605E+02	-13.97
Mn_pos (lb-in)	1.926E+07	1.771E+07	8.38	2.220E+07	2.484E+07	-11.22
Fn_neg (ln-in)	3.505E+04	3.736E+04	-6.38	3.879E+04	3.453E+04	11.63
Vn (lbs)	1.708E+05	1.726E+05	-1.02	1.708E+05	1.771E+05	-3.60
Mp (lb-in)	2.016E+07	1.934E+07	4.14	2.308E+07	2.633E+07	-13.13
DF	0.453	0.454	-0.14	0.660	0.660	0.00
DFV	0.596	0.596	0.00	0.660	0.660	0.00

Table 13: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	49.219	49.219	0.00	49.219	49.219	0.00
Dlstringer (lbs/in)	6.622	6.310	4.83	7.524	8.785	-15.46
Dldiaphragm (lbs/in)	0.228	0.228	0.00	0.228	0.228	0.00
Dlparapet (lbs/in)	7.031	7.031	0.00	7.031	7.031	0.00
wDL (lbs/in)	56.069	55.757	0.56	56.971	58.232	-2.19
wSDL (lbs/in)	7.031	7.031	0.00	7.031	7.031	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	9.189E+05	8.992E+05	2.16	9.337E+05	9.392E+05	-0.59
MDL_neg (lb-in)	-1.578E+06	-1.606E+06	-1.73	-1.604E+06	-1.677E+06	-4.47
MSDL_pos (lb-in)	1.152E+05	1.134E+05	1.60	1.152E+05	1.134E+05	1.60
MSDL_neg (lb-in)	-1.979E+05	-2.025E+05	-2.29	-1.979E+05	-2.025E+05	-2.29
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.674E+04	1.884E+04	-11.76	1.701E+04	1.958E+04	-14.02
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	7.088E+06	6.885E+06	2.90	7.088E+06	6.885E+06	2.90
MLL_neg1 (lb-in)	-5.633E+06	-5.762E+06	-2.27	-5.633E+06	-5.762E+06	-2.27
VLL_1 (lbs)	9.207E+04	9.195E+04	0.14	9.207E+04	9.195E+04	0.14
MLL_pos2 (lb-in)	3.210E+06	3.123E+06	2.77	4.678E+06	4.544E+06	2.90
MLL_neg2 (lb-in)	-2.551E+06	-2.614E+06	-2.41	-3.718E+06	-3.803E+06	-2.27
VLL_2(lbs)	5.490E+04	5.483E+04	0.14	6.077E+04	6.069E+04	0.14
M_pos (lb-in)	6.911E+06	6.731E+06	2.64	9.497E+06	9.268E+06	2.45
M_neg (lb-in)	6.685E+06	6.834E+06	-2.20	8.758E+06	9.005E+06	-2.78
V (lbs)	1.196E+05	1.242E+05	-3.75	1.302E+05	1.307E+05	-0.34

Table 14: Case 6 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
D (in.)	22.500	22.351	0.66	22.500	21.570	4.22
b_f (in.)	10.000	9.783	2.20	12.000	9.543	22.81
t_f (in.)	0.750	0.825	-9.47	0.750	1.215	-47.34
t_w (in.)	0.313	0.318	-1.75	0.313	0.315	-0.83
A (in^2)	22.031	23.240	-5.34	25.031	29.989	-18.02
Ix (in^4)	2.324E+03	2.463E+03	-5.79	2.730E+03	3.277E+03	-18.20
Iyc (in^4)	6.250E+01	6.433E+01	-2.88	1.080E+02	8.801E+01	20.39
Iyt (in^4)	6.250E+01	6.433E+01	-2.88	1.080E+02	8.801E+01	20.39
Ist (in^4)	7.293E+03	7.616E+03	-4.33	8.473E+03	9.770E+03	-14.22
Ilt (in^4)	5.498E+03	5.718E+03	-3.92	6.438E+03	7.315E+03	-12.75
yTnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBnc (in.)	12.000	12.000	0.00	12.000	12.000	0.00
yBst (in.)	24.423	24.257	0.68	24.588	24.024	2.32
yTst (in.)	0.423	0.257	48.92	-0.588	0.024	216.77
yBlt (in.)	20.314	20.094	1.09	20.539	19.794	3.69
yTly (in.)	3.686	3.906	-5.80	3.461	4.206	-19.43
STnc (in^3)	1.937E+02	2.052E+02	-5.79	2.275E+02	2.730E+02	-18.20
SBnc (in^3)	1.937E+02	2.052E+02	-5.79	2.275E+02	2.730E+02	-18.20
STst (in^3)	1.725E+04	2.968E+04	-52.97	1.440E+04	4.128E+05	-186.52
SBst (in^3)	2.986E+02	3.140E+02	-5.01	3.446E+02	4.067E+02	-16.53
STlt (in^3)	1.492E+03	1.464E+03	1.88	1.860E+03	1.739E+03	6.73
SBlt (in^3)	2.706E+02	2.845E+02	-5.01	3.135E+02	3.695E+02	-16.42
Mn_pos (lb-in)	1.926E+07	1.963E+07	-1.92	2.220E+07	2.528E+07	-13.01
Fn_neg (ln-in)	3.505E+04	3.455E+04	1.43	3.879E+04	3.436E+04	12.13
Vn (lbs)	1.708E+05	1.769E+05	-3.50	1.708E+05	1.737E+05	-1.65
Mp (lb-in)	2.016E+07	2.109E+07	-4.53	2.308E+07	2.690E+07	-15.26
DF	0.453	0.458	-1.01	0.660	0.660	0.00
DFV	0.596	0.596	0.00	0.660	0.660	0.00

Table 14: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	47.917	47.917	0.00	47.917	47.917	0.00
Dlstringer (lbs/in)	6.622	6.986	-5.34	7.524	9.014	-18.02
Dldiaphragm (lbs/in)	0.228	0.228	0.00	0.228	0.228	0.00
Dlparapet (lbs/in)	3.125	3.125	0.00	3.125	3.125	0.00
wDL (lbs/in)	54.767	55.131	-0.66	55.669	57.159	-2.64
wSDL (lbs/in)	3.125	3.125	0.00	3.125	3.125	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	8.975E+05	8.891E+05	0.94	9.123E+05	9.219E+05	-1.04
MDL_neg (lb-in)	-1.542E+06	-1.588E+06	-2.95	-1.567E+06	-1.646E+06	-4.93
MSDL_pos (lb-in)	5.121E+04	5.040E+04	1.60	5.121E+04	5.040E+04	1.60
MSDL_neg (lb-in)	-8.797E+04	-9.000E+04	-2.29	-8.797E+04	-9.000E+04	-2.29
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.636E+04	1.748E+04	-6.63	1.663E+04	1.809E+04	-8.41
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	7.088E+06	6.885E+06	2.90	7.088E+06	6.885E+06	2.90
MLL_neg1 (lb-in)	-5.633E+06	-5.762E+06	-2.27	-5.633E+06	-5.762E+06	-2.27
VLL_1 (lbs)	9.207E+04	9.195E+04	0.14	9.207E+04	9.195E+04	0.14
MLL_pos2 (lb-in)	3.210E+06	3.150E+06	1.89	4.678E+06	4.544E+06	2.90
MLL_neg2 (lb-in)	-2.551E+06	-2.636E+06	-3.28	-3.718E+06	-3.803E+06	-2.27
VLL_2(lbs)	5.490E+04	5.483E+04	0.14	6.077E+04	6.069E+04	0.14
M_pos (lb-in)	6.804E+06	6.687E+06	1.73	9.391E+06	9.167E+06	2.41
M_neg (lb-in)	6.502E+06	6.711E+06	-3.17	8.574E+06	8.826E+06	-2.89
V (lbs)	1.177E+05	1.222E+05	-3.73	1.283E+05	1.288E+05	-0.40

Table 15: Case 7 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
D (in.)	93.500	91.174	2.52	93.500	93.467	0.04
b_f (in.)	19.000	16.023	17.00	18.000	23.180	-25.16
t_f (in.)	1.250	2.413	-63.50	1.250	1.266	-1.31
t_w (in.)	0.750	0.632	17.15	0.625	0.681	-8.54
A (in^2)	117.625	134.904	-13.69	103.438	122.342	-16.75
Ix (in^4)	1.577E+05	2.092E+05	-28.09	1.436E+05	1.781E+05	-21.44
Iyc (in^4)	7.145E+02	8.271E+02	-14.62	6.075E+02	1.315E+03	-73.57
Iyt (in^4)	7.145E+02	8.271E+02	-14.62	6.075E+02	1.315E+03	-73.57
Ist (in^4)	3.132E+05	3.748E+05	-17.91	2.562E+05	2.980E+05	-15.07
Ilt (in^4)	2.336E+05	2.875E+05	-20.68	1.944E+05	2.303E+05	-16.91
yTnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBst (in.)	73.058	71.271	2.48	68.662	66.600	3.05
yTst (in.)	22.942	24.729	-7.50	27.338	29.400	-7.27
yBlt (in.)	60.251	59.011	2.08	57.337	56.117	2.15
yTly (in.)	35.749	36.989	-3.41	38.663	39.883	-3.11
STnc (in^3)	3.285E+03	4.359E+03	-28.09	2.991E+03	3.710E+03	-21.44
SBnc (in^3)	3.285E+03	4.359E+03	-28.09	2.991E+03	3.710E+03	-21.44
STst (in^3)	1.365E+04	1.516E+04	-10.45	9.373E+03	1.014E+04	-7.82
SBst (in^3)	4.287E+03	5.259E+03	-20.37	3.732E+03	4.474E+03	-18.09
STlt (in^3)	6.534E+03	7.772E+03	-17.30	5.029E+03	5.776E+03	-13.82
SBlt (in^3)	3.877E+03	4.871E+03	-22.73	3.391E+03	4.105E+03	-19.04
Mn_pos (lb-in)	2.769E+08	3.325E+08	-18.22	2.164E+08	2.479E+08	-13.56
Fn_neg (ln-in)	3.594E+04	3.327E+04	7.72	3.545E+04	4.031E+04	-12.84
Vn (lbs)	5.958E+05	3.645E+05	48.17	3.448E+05	4.454E+05	-25.46
Mp (lb-in)	2.912E+08	3.325E+08	-13.24	2.443E+08	2.850E+08	-15.38
DF	0.622	0.634	-1.93	0.479	0.483	-0.87
DFV	0.814	0.814	0.00	0.489	0.489	0.00

Table 15: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	65.625	65.625	0.00	65.625	65.625	0.00
Dlstringer (lbs/in)	35.356	40.549	-13.69	31.091	36.773	-16.75
Dldiaphragm (lbs/in)	0.120	0.122	-1.30	0.120	0.122	-1.30
Dlparapet (lbs/in)	9.375	9.375	0.00	9.375	9.375	0.00
wDL (lbs/in)	101.101	106.296	-5.01	96.836	102.520	-5.70
wSDL (lbs/in)	9.375	9.375	0.00	9.375	9.375	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	2.612E+07	2.743E+07	-4.91	2.501E+07	2.646E+07	-5.60
MDL_neg (lb-in)	-4.652E+07	-4.898E+07	-5.15	-4.456E+07	-4.724E+07	-5.85
MSDL_pos (lb-in)	2.422E+06	2.419E+06	0.10	2.422E+06	2.419E+06	0.10
MSDL_neg (lb-in)	-4.314E+06	-4.320E+06	-0.14	-4.314E+06	-4.320E+06	-0.14
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.213E+05	1.388E+05	-13.47	1.162E+05	1.343E+05	-14.46
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	5.253E+07	5.251E+07	0.03	5.253E+07	5.251E+07	0.03
MLL_neg1 (lb-in)	-4.819E+07	-5.931E+07	-20.68	-4.819E+07	-5.931E+07	-20.68
VLL_1 (lbs)	1.561E+05	1.720E+05	-9.65	1.561E+05	1.720E+05	-9.65
MLL_pos2 (lb-in)	3.266E+07	3.329E+07	-1.90	2.515E+07	2.536E+07	-0.84
MLL_neg2 (lb-in)	-2.997E+07	-3.760E+07	-22.59	-2.308E+07	-2.865E+07	-21.55
VLL_2(lbs)	1.521E+05	1.400E+05	8.24	9.124E+04	8.403E+04	8.24
M_pos (lb-in)	9.283E+07	9.557E+07	-2.91	7.831E+07	8.048E+07	-2.73
M_neg (lb-in)	1.160E+08	1.324E+08	-13.24	1.015E+08	1.146E+08	-12.14
V (lbs)	4.318E+05	4.533E+05	-4.86	3.189E+05	3.132E+05	1.82

Table 16: Case 8 Results Comparison

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
D (in.)	93.500	89.116	4.80	93.500	92.111	1.50
b_f (in.)	19.000	16.008	17.10	19.000	16.444	14.42
t_f (in.)	1.250	3.442	-93.44	1.250	1.944	-43.47
t_w (in.)	0.750	1.084	-36.45	0.625	0.627	-0.29
A (in^2)	117.625	206.834	-54.99	105.938	121.681	-13.83
Ix (in^4)	1.577E+05	3.001E+05	-62.21	1.492E+05	1.823E+05	-19.96
Iyc (in^4)	7.145E+02	1.177E+03	-48.88	7.145E+02	7.204E+02	-0.83
Iyt (in^4)	7.145E+02	1.177E+03	-48.88	7.145E+02	7.204E+02	-0.83
Ist (in^4)	3.132E+05	4.957E+05	-45.13	2.759E+05	3.164E+05	-13.69
Ilt (in^4)	2.336E+05	3.844E+05	-48.82	2.084E+05	2.431E+05	-15.35
yTnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBnc (in.)	48.000	48.000	0.00	48.000	48.000	0.00
yBst (in.)	73.058	65.944	10.24	70.677	68.912	2.53
yTst (in.)	22.942	30.056	-26.84	25.323	27.088	-6.74
yBlt (in.)	60.251	55.746	7.77	58.616	57.491	1.94
yTly (in.)	35.749	40.254	-11.85	37.384	38.509	-2.97
STnc (in^3)	3.285E+03	6.252E+03	-62.21	3.108E+03	3.797E+03	-19.96
SBnc (in^3)	3.285E+03	6.252E+03	-62.21	3.108E+03	3.797E+03	-19.96
STst (in^3)	1.365E+04	1.649E+04	-18.85	1.089E+04	1.168E+04	-6.97
SBst (in^3)	4.287E+03	7.516E+03	-54.73	3.903E+03	4.591E+03	-16.21
STlt (in^3)	6.534E+03	9.551E+03	-37.51	5.575E+03	6.312E+03	-12.40
SBlt (in^3)	3.877E+03	6.896E+03	-56.05	3.556E+03	4.228E+03	-17.28
Mn_pos (lb-in)	2.769E+08	4.153E+08	-39.99	2.383E+08	2.716E+08	-13.03
Fn_neg (ln-in)	3.594E+04	3.207E+04	11.37	3.665E+04	3.362E+04	8.62
Vn (lbs)	5.958E+05	1.888E+06	-104.04	3.448E+05	3.528E+05	-2.31
Mp (lb-in)	2.912E+08	4.771E+08	-48.40	2.576E+08	2.938E+08	-13.11
DF	0.622	0.600	3.57	0.600	0.600	0.00
DFV	0.814	0.814	0.00	0.600	0.600	0.00

Table 16: Cont.

Parameter	Interior			Exterior		
	Hand Value	RAMPS Value	Percent Difference	Hand Value	RAMPS Value	Percent Difference
Dldeck (lbs/in)	71.875	71.875	0.00	71.875	71.875	0.00
Dlstringer (lbs/in)	35.356	62.170	-54.99	31.843	36.575	-13.83
Dldiaphragm (lbs/in)	0.120	0.122	-1.30	0.120	0.122	-1.30
Dlparapet (lbs/in)	4.688	4.688	0.00	4.688	4.688	0.00
wDL (lbs/in)	107.351	134.166	-22.21	103.838	108.571	-4.46
wSDL (lbs/in)	4.688	4.688	0.00	4.688	4.688	0.00
wSDW (lbs/in)	0.000	0.000	0.00	0.000	0.000	0.00
MDL_pos (lb-in)	2.773E+07	3.462E+07	-22.10	2.682E+07	2.802E+07	-4.35
MDL_neg (lb-in)	-4.940E+07	-6.182E+07	-22.35	-4.778E+07	-5.003E+07	-4.60
MSDL_pos (lb-in)	1.211E+06	1.210E+06	0.10	1.211E+06	1.210E+06	0.10
MSDL_neg (lb-in)	-2.157E+06	-2.160E+06	-0.14	-2.157E+06	-2.160E+06	-0.14
MSDW_pos (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MSDW_neg (lb-in)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
VDL (lbs)	1.288E+05	1.666E+05	-25.62	1.246E+05	1.359E+05	-8.71
VDW (lbs)	0.000E+00	0.000E+00	0.00	0.000E+00	0.000E+00	0.00
MLL_pos1 (lb-in)	5.253E+07	5.251E+07	0.03	5.253E+07	5.251E+07	0.03
MLL_neg1 (lb-in)	-4.819E+07	-5.931E+07	-20.68	-4.819E+07	-5.931E+07	-20.68
VLL_1 (lbs)	1.561E+05	1.720E+05	-9.65	1.561E+05	1.720E+05	-9.65
MLL_pos2 (lb-in)	3.266E+07	3.151E+07	3.60	3.152E+07	3.151E+07	0.03
MLL_neg2 (lb-in)	-2.997E+07	-3.559E+07	-17.14	-2.892E+07	-3.559E+07	-20.68
VLL_2(lbs)	1.521E+05	1.032E+05	38.32	1.120E+05	1.032E+05	8.24
M_pos (lb-in)	9.334E+07	9.993E+07	-6.82	9.020E+07	9.167E+07	-1.62
M_neg (lb-in)	1.169E+08	1.423E+08	-19.58	1.130E+08	1.275E+08	-12.05
V (lbs)	4.341E+05	3.888E+05	11.01	3.588E+05	3.504E+05	2.36

The “one-to-one” validation approach was very effective, but in order to validate all parts of the possible design paths a line by line analysis was also performed. This analysis was used to ensure that there were no typos and all appropriate equations were being calculated properly. Several errors were found this way, all of which are include in a detailed log provided in Appendix B. There were two errors that had a significant effect on the automated sizing. The first was associated with a process that was originally used to merge interior and exterior girder designs, which was ultimately abandoned to have separate interior and exterior girder designs. The second error was a constraint that forced one of the girder designs to be greater than (instead of less than) the non-compact slenderness limit defined by AASHTO LRFD Eqn. 6.10.6.2.2-1. This caused the software to incorrectly determine compact from non-compact in the negative moment regions. Many errors have since been addressed and the corrected results are used in this report.

To further validate the process, the flow of the software was compared to the flow charts provided in AASHTO LRFD Specs Section C.6. It was apparent that the automated member-sizing software calculates and evaluates all necessary constraints, with a work flow similar to that represented in the flow charts provided by AASHTO.

Chapter 6

CONCLUSION

A one-to-one validation approach was used to validate the girder designs and all associated calculations performed by the software RAMPS. Eight bridge cases were analyzed in order to prove that RAMPS appropriately sized girders in an automated fashion according following all AASHTO LRFD Specifications. The test bed of bridges consisted of both simple and multiple-span bridges with composite steel I-girders. The values and ranges of the parameters were selected in an attempt to test the RAMPS program at the extremum of the parameters ranges that can most greatly affect a bridge design. The results from RAMPS were compared directly with a load analysis performed using STAAD, and a design spreadsheet.

The comparisons were used to identify any numerical discrepancies and the possible underlying causes or assumptions leading to these differences. After a comparison of results between RAMPS and hand designs, it was found that the RAMPS software performs an accurate single line girder load analysis and can design a valid bridge that passes all checked AASHTO LRFD requirements. By direct comparison, it was found that the cross-sectional dimensions generated by the RAMPS software weren't always as efficient as possible. A reason for this may be that the optimization function used in the program is getting caught in a local minimum. However, in the controlling mode of flexural capacity, the RAMPS calculations and the hand designs were very close. Overall, RAMPS has the ability to quickly generate a valid steel composite I-girder design, while following all LRFD requirements. The constraints used to limit the RAMPS designs work well to force a valid design. Since this program is still being refined, the results show that the RAMPS program will be able generate valid designs even if additional AASHTO LRFD constraints are added.

REFERENCES

American Association of State Highway Transportation Officials. (2013). AASHTO LRFD Bridge Design Specifications (6th ed.). Washington, D.C.

Bentley Systems, Inc. (2014). STAAD (SELECTseries 5) [Computer Software]. Exton, PA: Bentley Systems, Inc.

Drexel University (2015). *Quarterly Progress Report to the NCHRP.* Unpublished internal document.

“fmincon”. < http://www.mathworks.com/help/optim/ug/fmincon.html> (2015)

Appendix A

RAMPS DESIGN PROCESS

Input Geometry & Material Properties (from Task 2.1.1)

Assignments:

- Bridge Type (Steel, Pre-stressed)
- Number of Spans
- Span Length
- Road Width
- New/Far Skew
- Deck Thickness
- Sidewalk Height
- Sidewalk Widths
- Barrier Height
- Barrier Width
- Concrete Deck Strength
- Concrete Barrier Strength
- Concrete Sidewalk Strength
- Steel Strength

↓

Diaphragm Configuration (Manual or Automated)

- Select Diaphragm Configuration: Parallel to Skew, Normal to Girder, Staggered
- Select Diaphragm Type manually or choose "Automatically Assign"
- Choose number of interior diaphragm lines based on bridge span length

Assignments :

- Number of Diaphragms
- Diaphragm Spacing
- Diaphragm Dimensions
- Diaphragm Type

↓

Girder Sizing

- Choose Design Method and Design Truck (Default = LRFD and HL-93).
- Assign girder criteria: Span-to-Depth, Number of Girders, Girder Spacing
- Choose levels of composite action
- Assign wearing surface thickness
- For negative moment regions within multi-girder steel bridges, select whether or not to build section with cover plate
- Input dimensions manually of run sizing algorithm to size and evaluate plate girder section against AASHTO design constraints

Assignments (Input or Outputs):

- Number of Girders
- Girder Spacing
- Span-to-Depth
- Composite action
- Wearing surface thickness
- Cover plate length (optional)
- Flange Width
- Flange Thickness
- Web Thickness
- Rolled Section dimensions

Figure A-1: RAMPS Design Flowchart

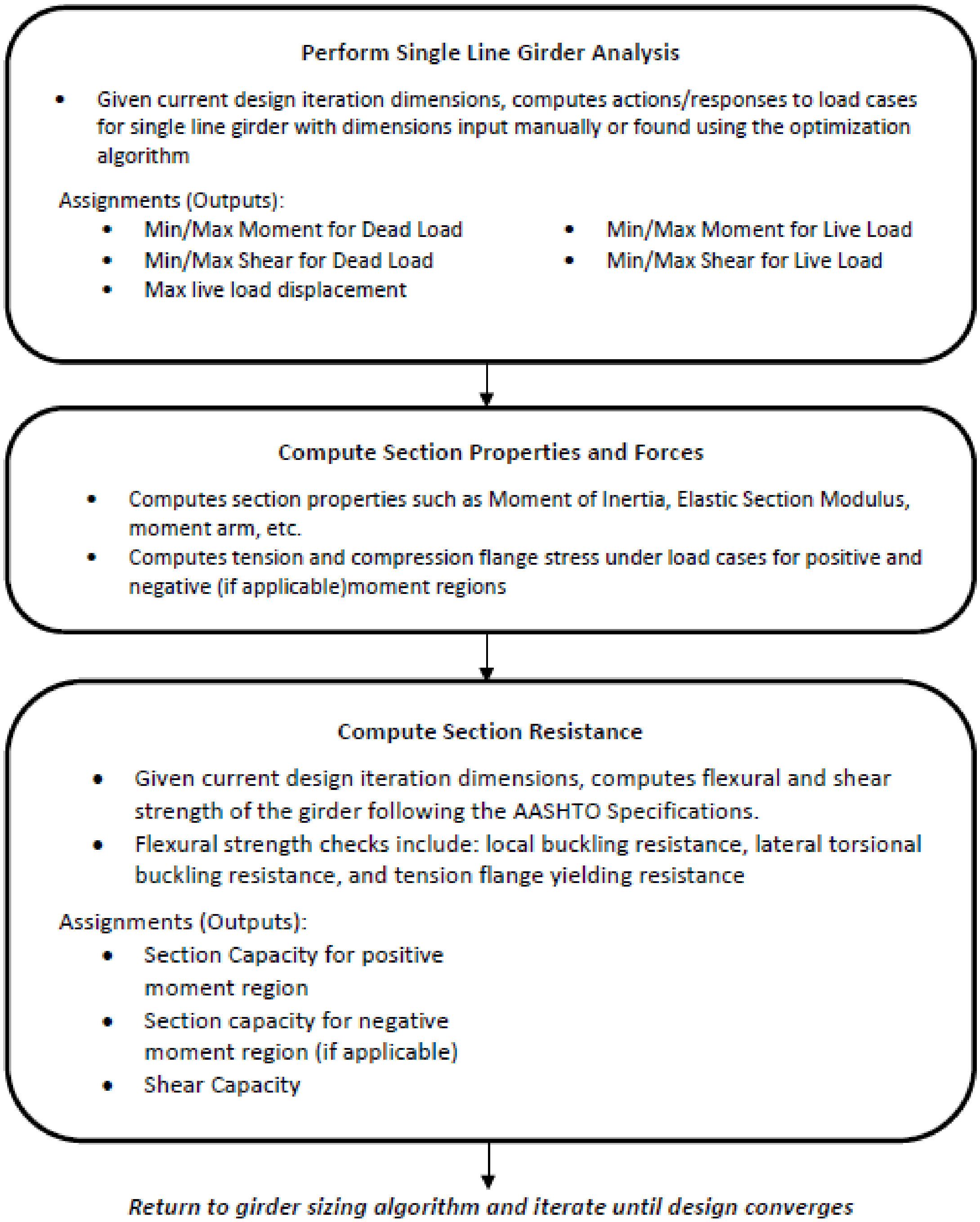

Figure A-1: Cont.

Appendix B

STEP-BY-STEP SOFTWARE FLOWCHART

The following flow charts depict the step-by-step process taken by the software. These are provided in a similar fashion to the flow charts provided in AASHTO Appendix C6.

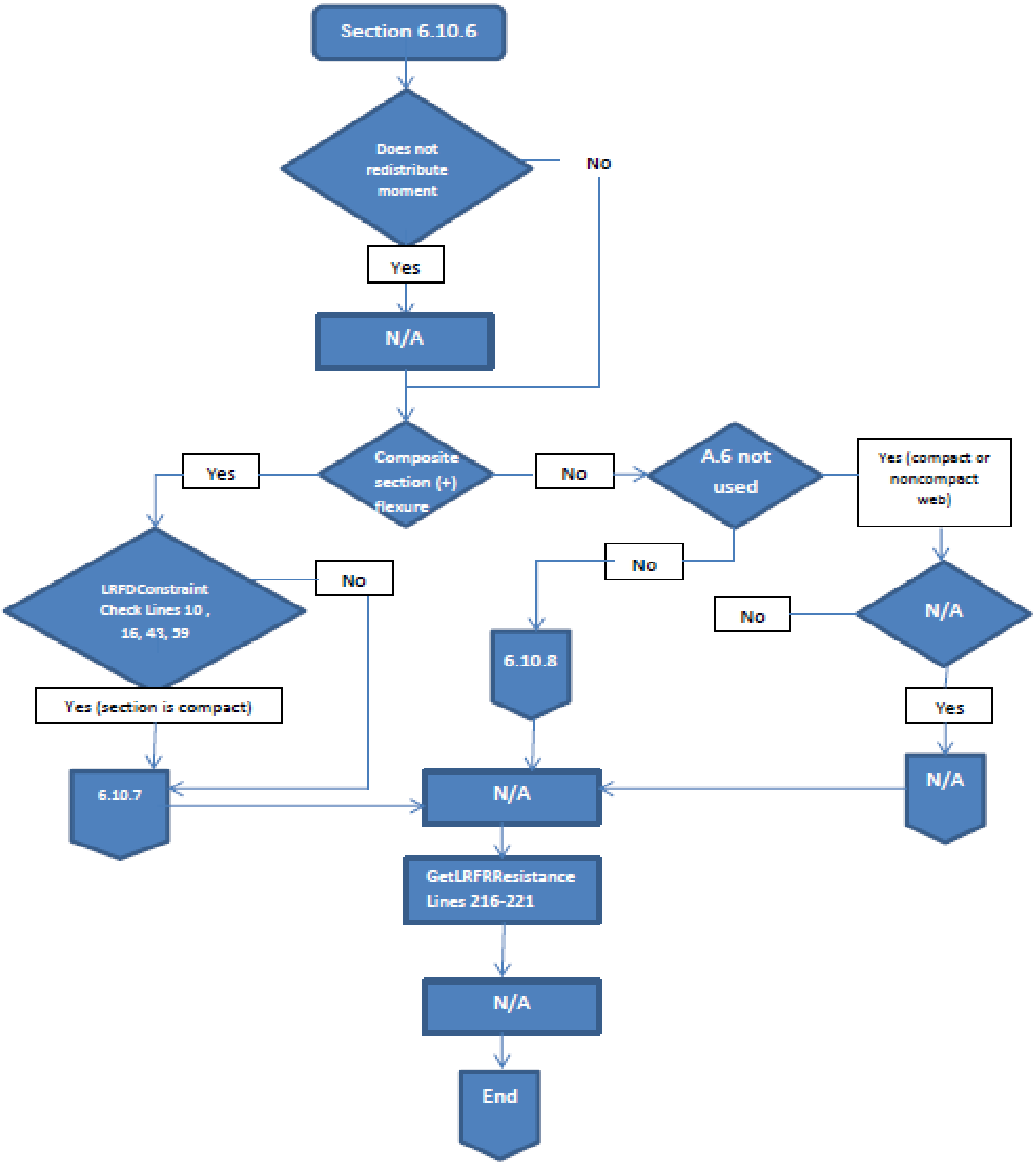

Figure B-1: Flowchart for LRFD Article 6.10.6 - Strength Limit State

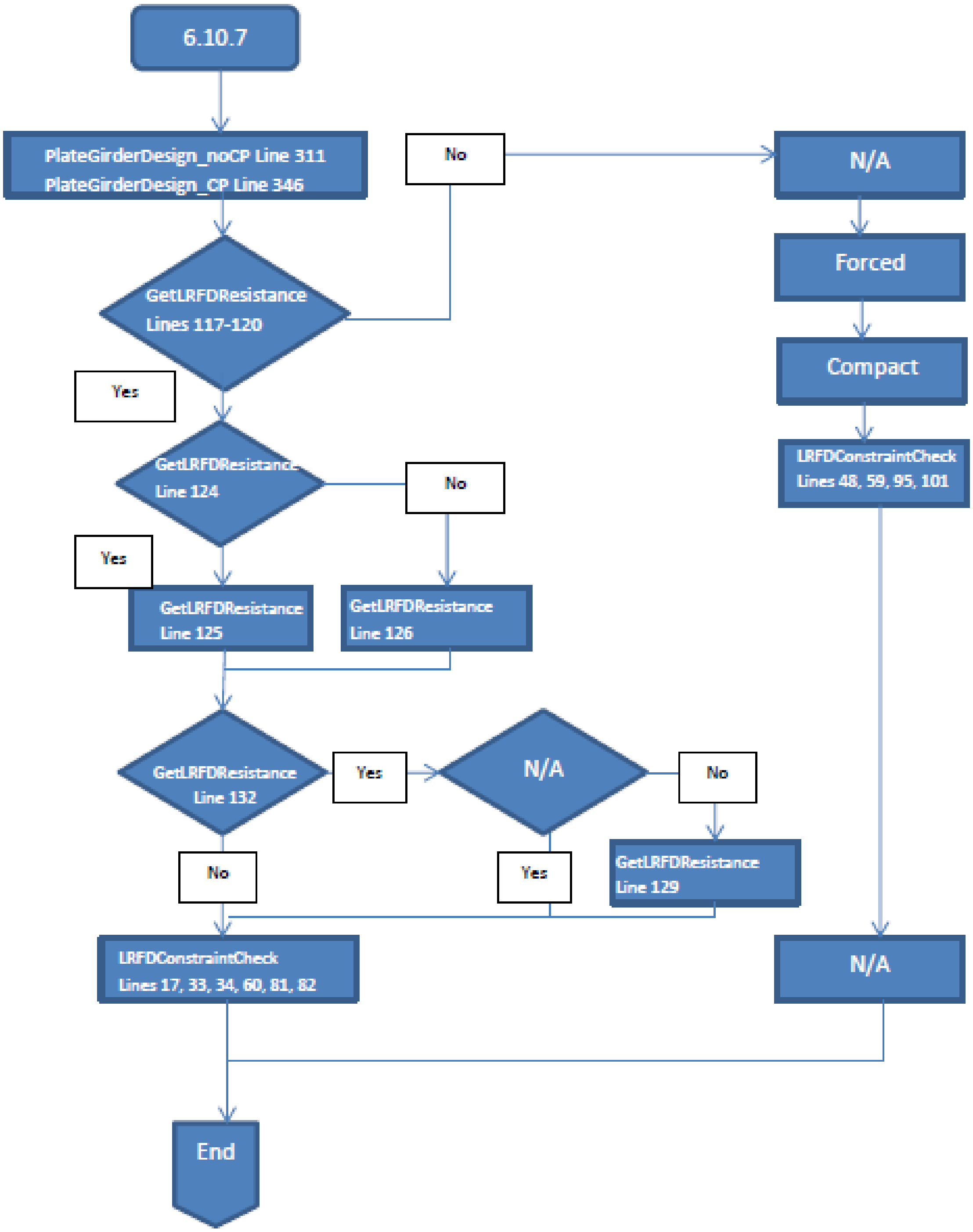

Figure B-2: Flowchart for LRFD Article 6.10.7

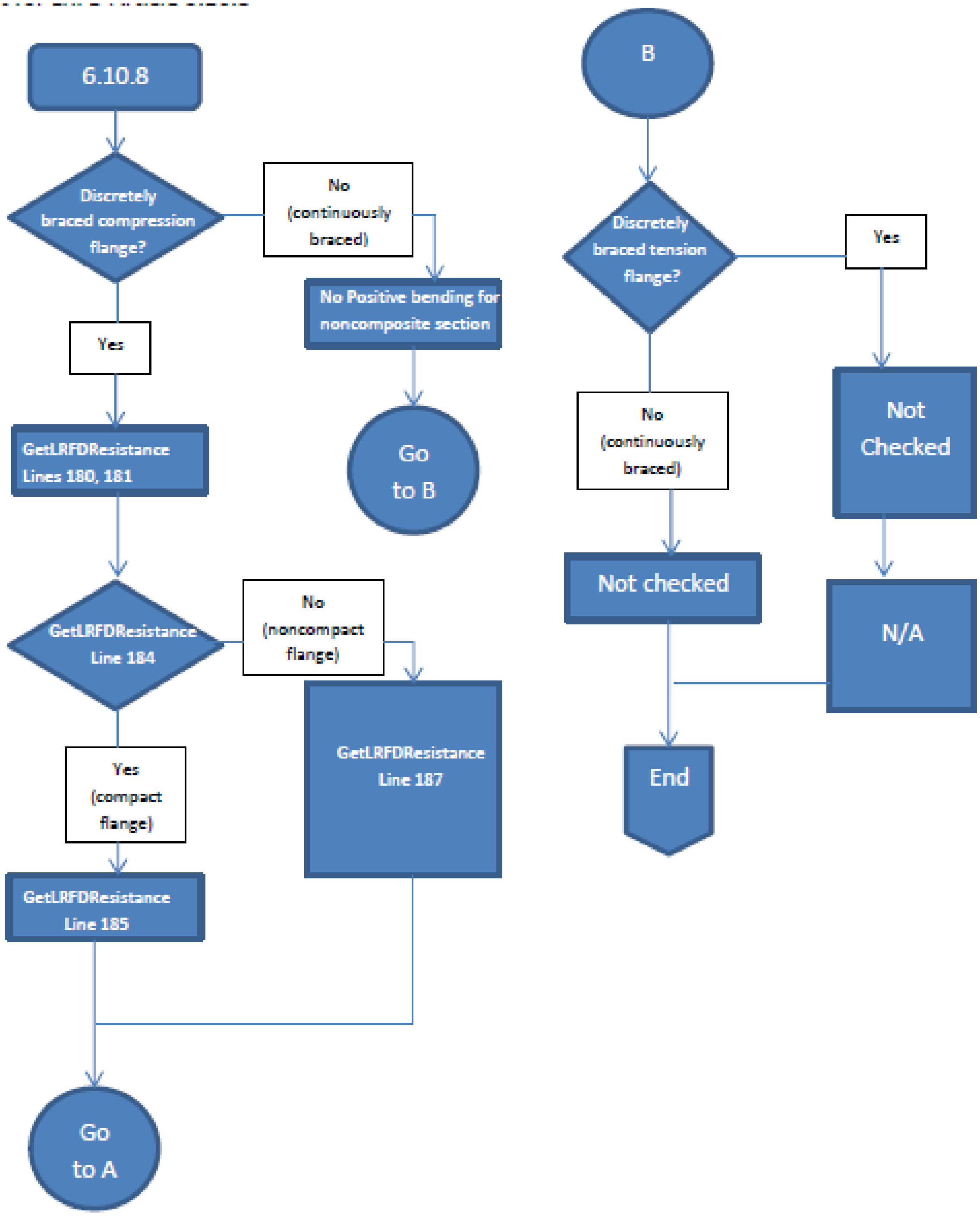

Figure B-3: Flowchart for LRFD Article 6.10.8

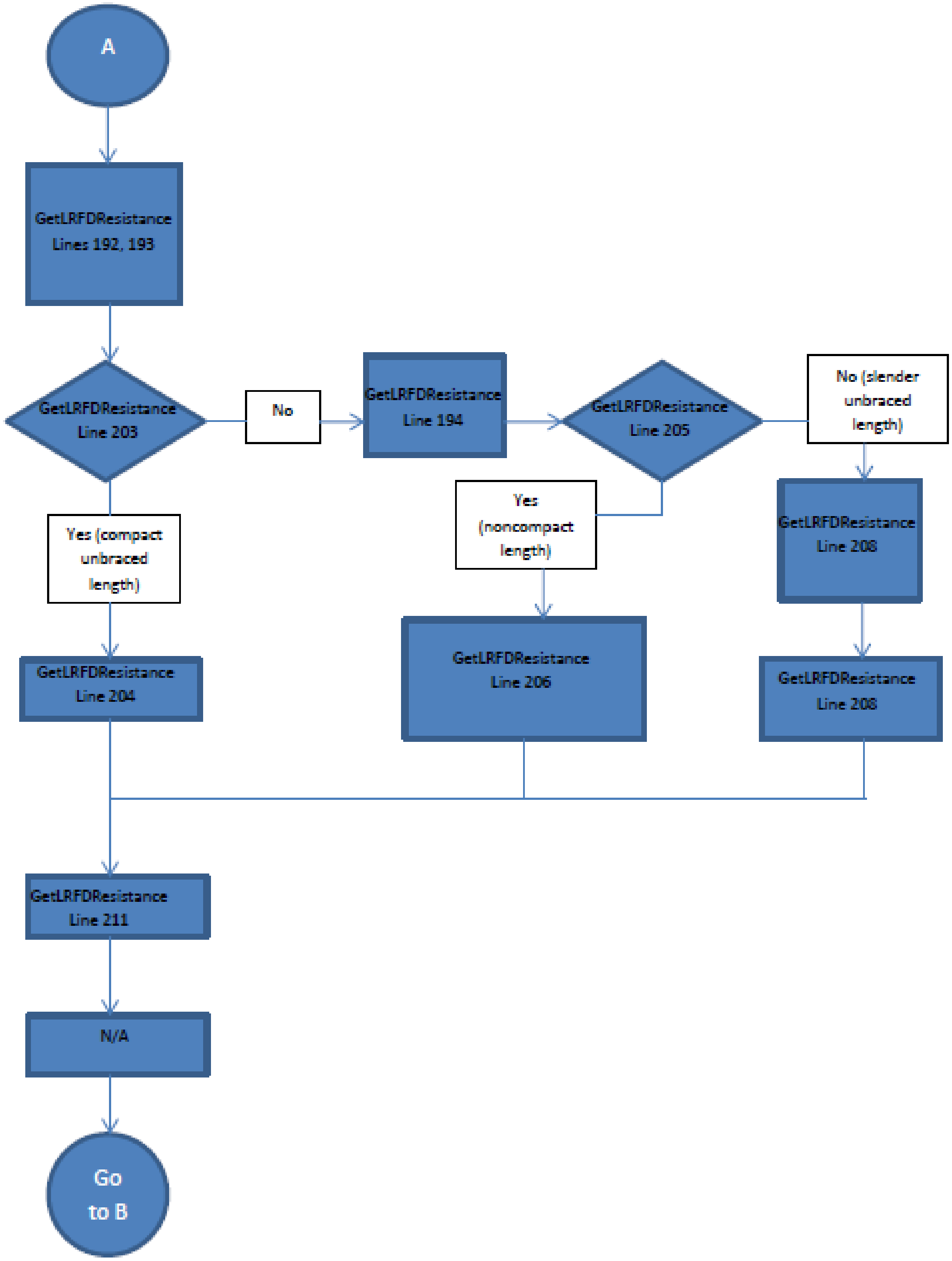

Figure B-3: Cont.

Appendix C

RAMPS COMMENT FORMS

Project:	NCHRP Project 12-103	Date:	3/19/2015
Document Considered:	RAMPS Matlab Files	Review Type:	Peer Review
Principal Investigator:	Frank Moon	Reviewer:	Michael Berti
Responsible Professional(s):	Dave Masceri	Project Phase:	Phase II

Script	Line No.	Comment No.	Reviewer Comment	Respond. Initials	Responsible Professional Response	Status	Date Approved	Reviewer App'd
GetLRFDResistance	216	1	Error in simplification of AASHTO LRFD Eqn 6.10.9.3.2-4					
GetLRFDResistance	218	2	Error in simplification of AASHTO LRFD Eqn 6.10.9.3.2-5 substituted into Eqn 6.10.9.2-2					
GetLRFDResistance	219	3	Error in simplification of AASHTO LRFD Eqn 6.10.9.3.2-6 substituted into Eqn 6.10.9.2-2					
GetSectionForces	19	4	Deck width calculation based only on girder spacing and does not properly calculate the width.					

Script	Line No.	Comment No.	Reviewer Comment	Respond. Initials	Responsible Professional Response	Status	Date Approved	Reviewer App'd
GetSectionForces	51	5	Future wearing surface dead load calculation is done only with respect to the interior effective width instead of considering the entire width of the roadway. Also, the calculation is performed only with the density of concrete. There is no consideration for the future wearing surface being a different material.					
GetStructureConfig	114	6	The overhang is calculated as the half the girder spacing. The actual overhang length can be different, depending on the RAMPS inputs.					
GirderSizing	59	7	RAMPS selects the largest total cross-sectional area when choosing to use the interior or an exterior beam dimensions. However, RAMPS should choose the largest flange area and largest web area separately with the final section used consisting the largest flange and web areas.					
LRFDConstraintCheck	32	8	This constraint currently forces the section to exceed noncompact slenderness limit defined by Eqn 6.10.6.2.2-1					
LRFDConstraintCheck	80	9	See Comment 8					
LRFDConstraintCheck	117	10	See Comment 8					

Script	Line No.	Comment No.	Reviewer Comment	Respond. Initials	Responsible Professional Response	Status	Date Approved	Reviewer App'd
LRFDDistFact	38	11	Typo in the equation listed in Table 4.6.2.2.2b-1					
LRFDDistFact	N/A	12	In beam-slab bridges with diaphragms or cross-frames, the distribution factor must not be less than that which assumes the cross-section deflects and rotates as a rigid section as stated in 4.6.2.2.2d. This is currently not considered.					

Project:	NCHRP Project 12-103	Date:	4/6/2015
Document Considered:	LRFDConstraintCheck.m	Review Type:	Peer Review
Principal Investigator:	Frank Moon	Reviewer:	Michael Berti
Responsible Professional(s):	Dave Masceri, Nick Romano	Project Phase:	Phase II

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
1	function ArgOut = LRFDConstraintCheck(Parameters)				
2					
3	if Parameters.Spans == 1				
4	if Parameters.Beam.Comp == 1;				
5	% Constraints for compact section				
6	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);	Makes sure overall depth is greater than the suggested minimum overall depth for a constant depth superstructure.	Table 2.5.2.6.3-1	No	Uses value from continuous span, not simple span.
7	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;	Makes sure depth of I-Beam portion of composite I-Beam is greater than the suggested minimum I-Beam depth for a constant depth superstructure.	Table 2.5.2.6.3-1	No	Uses value from continuous span, not simple span.
8	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;	Ductility requirement that compact and noncompact sections must satisfy.	6.10.7.3	Yes	
9	c(4) = 0.3125 - Parameters.Beam.tw;	Minimum thickness of steel.	6.7.3	Yes	
10	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;	Web cross section proportional limit.	6.10.2.1	Yes	
11	c(6) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;	Flange cross section proportional limit.	6.10.2.2	Yes	
12	c(7) = Parameters.Beam.ind/6 - Parameters.Beam.bf;	Flange cross section proportional limit.	6.10.2.2	Yes	
13	c(8) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;	Flange cross section proportional limit.	6.10.2.2	Yes	

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
14	c(9) = Parameters.Demands.LRFD.fbc_pos(2, :)-0.95*Parameters.Beam.Fy;	Makes sure flange stress at section under consideration is below specified maximum stress.	Eqn. 6.10.4.2.2-1	Yes	
15	c(10) = Parameters.Demands.LRFD.fbt_pos(2,:)-0.95*Parameters.Beam.Fy;	Makes sure flange stress at section under consideration is below specified maximum stress.	Eqn. 6.10.4.2.2-2	Yes	
16	c(11) = 2*Parameters.Beam.Dcp/Parameters.Beam.tw-3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy);	Makes sure the composite section is below the web slenderness limit.	6.10.6.2.2	Yes	
17	c(12) = max(Parameters.Demands.LRFD.M_pos)-Parameters.Beam.Mn_pos;	Makes sure that the nominal flexural resistance is greater than the ultimate positive applied moment.	6.10.7.1	Yes	
18	c(13) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;	Makes sure that the nominal shear resistance is greater than the ultimate shear on the section.	6.10.9.1	Yes	
19	c(14) = Parameters.Demands.LRFD.fbc_neg(2, :)-Parameters.Beam.Fcrw;	Ensures that theoretical web-bend buckling will not occur under Service II loads.	Eqn. 6.10.3.2.1-3	Yes	
20	c(15) = Parameters.Demands.LRFD.fbc_neg(1, :)-Parameters.Beam.Fn_neg;	Ensures that the applied flange stress in negative bending is less than the negative flexural resistance.	6.10.8.1.1	Yes	
21	c(16) = Parameters.Demands.LRFD.fbt_neg(1, :)-Parameters.Beam.Fy;	Ensures that the applied flange stress in negative bending is less than the yield stress of steel.	6.10.8.1.2	Yes	
22	else				
23	% Constraints for non-compact section				
24	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);	See Comment Line 6			

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
25	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;	See Comment Line 7			
26	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;	See Comment Line 8			
27	c(4) = 0.3125 - Parameters.Beam.tw;	See Comment Line 9			
28	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;	See Comment Line 10			
29	c(6) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;	See Comment Line 11			
30	c(7) = Parameters.Beam.ind/6 - Parameters.Beam.bf;	See Comment Line 12			
31	c(8) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;	See Comment Line 13			
32	c(9) = 3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy)-2*Parameters.Beam.Dcp/Parameters.Beam.tw;	Makes sure that section exceeds web slenderness limit.	6.10.6.2.2	No	This is only applicable to composite sections in positive flexure. This constraint is not needed for the noncomposite section.
33	c(10) = Parameters.Demands.LRFD.fbc_pos(1,:)-Parameters.Beam.Fn_pos;	Ensures that the noncomposite nominal flexural resistance is greater that the	6.10.8.1.1		
34	c(11) = Parameters.Demands.LRFD.fbt_pos(1,:)-Parameters.Beam.Fn_pos;		6.10.8.1.2		
35	c(12) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;				
36	c(13) = Parameters.Demands.LRFD.fbc_neg(2,:)-Parameters.Beam.Fcrw;				
37	c(14) = Parameters.Demands.LRFD.fbc_neg(1,:)-Parameters.Beam.Fn_neg;				
38	c(15) = Parameters.Demands.LRFD.fbt_neg(1,:)-Parameters.Beam.Fy;				
39	end				
40	else % Spans > 1				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
41	if Parameters.Beam.CoverPlate.t > 0				
42	if Parameters.Beam.Comp == 1				
43	% Constraints for Compact Section				
44	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);	Makes sure overall depth is greater than the suggested minimum overall depth for a constant depth superstructure.	Table 2.5.2.6.3-1	Yes	
45	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;	Makes sure depth of I-Beam portion of composite I-Beam is greater than the suggested minimum I-Beam depth for a constant depth superstructure.	Table 2.5.2.6.3-1	Yes	
46	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;				
47	c(4) = 0.3125 - Parameters.Beam.tw;				
48	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;				
49	c(6) = Parameters.Beam.CoverPlate.ind/Parameters.Beam.tw - 150;				
50	c(7) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;				
51	c(8) = Parameters.Beam.d/6 - Parameters.Beam.bf;				
52	c(9) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;				
53	c(10) = Parameters.Beam.CoverPlate.bf/(2*Parameters.Beam.CoverPlate.tf) - 12;				
54	c(11) = 1.1*Parameters.Beam.CoverPlate.tw - Parameters.Beam.CoverPlate.tf;				
55	c(12) = Parameters.Beam.CoverPlate.tf - 3*Parameters.Beam.tf;	Cover plate proportional limit.	6.10.12.1	Yes	
56	c(13) = Parameters.Beam.tf - Parameters.Beam.CoverPlate.tf;				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
57	c(14) = Parameters.Demands.LRFD.fbc_pos(2, :)-0.95*Parameters.Beam.Fy;				
58	c(15) = Parameters.Demands.LRFD.fbt_pos(2,:)-0.95*Parameters.Beam.Fy;				
59	c(16) = 2*Parameters.Beam.Dcp/Parameters.Beam.tw-3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy);				
60	c(17) = max(Parameters.Demands.LRFD.M_pos)-Parameters.Beam.Mn_pos;				
61	c(18) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;				
62	c(19) = Parameters.Demands.LRFD.fbc_neg(2, :)-Parameters.Beam.Fcrw;				
63	c(20) = Parameters.Demands.LRFD.fbc_neg(1, :)-Parameters.Beam.Fn_neg;				
64	c(21) = Parameters.Demands.LRFD.fbt_neg(1, :)-Parameters.Beam.Fy;				
65	else				
66	% Constraints for non-compact section				
67	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);				
68	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;				
69	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;				
70	c(4) = 0.3125 - Parameters.Beam.tw;				
71	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;				
72	c(6) = Parameters.Beam.CoverPlate.ind/Parameters.Beam.tw - 150;				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
73	c(7) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;				
74	c(8) = Parameters.Beam.d/6 - Parameters.Beam.bf;				
75	c(9) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;				
76	c(10) = Parameters.Beam.CoverPlate.bf/(2*Parameters.Beam.CoverPlate.tf) - 12;				
77	c(11) = 1.1*Parameters.Beam.CoverPlate.tw - Parameters.Beam.CoverPlate.tf;				
78	c(12) = Parameters.Beam.CoverPlate.tf - 3*Parameters.Beam.tf;				
79	c(13) = Parameters.Beam.tf - Parameters.Beam.CoverPlate.tf;				
80	c(14) = 3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy)-2*Parameters.Beam.Dcp/Parameters.Beam.tw;				
81	c(15) = max(Parameters.Demands.LRFD.fbc_pos(1,:))-Parameters.Beam.Fn_pos;				
82	c(16) = max(Parameters.Demands.LRFD.fbt_pos(1,:))-Parameters.Beam.Fn_pos;				
83	c(17) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;				
84	c(18) = Parameters.Demands.LRFD.fbc_neg(2,:)-Parameters.Beam.Fcrw;				
85	c(19) = Parameters.Demands.LRFD.fbc_neg(1,:)-Parameters.Beam.Fn_neg;				
86	c(20) = Parameters.Demands.LRFD.fbt_neg(1,:)-Parameters.Beam.Fy;				
87	end				
88	else % no cover plate				
89	if Parameters.Beam.Comp == 1;				
90	% Constraints for compact section				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
91	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);				
92	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;				
93	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;				
94	c(4) = 0.3125 - Parameters.Beam.tw;				
95	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;				
96	c(6) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;				
97	c(7) = Parameters.Beam.ind/6 - Parameters.Beam.bf;				
98	c(8) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;				
99	c(9) = Parameters.Demands.LRFD.fbc_pos(2,:)-0.95*Parameters.Beam.Fy;				
100	c(10) = Parameters.Demands.LRFD.fbt_pos(2,:)-0.95*Parameters.Beam.Fy;				
101	c(11) = 2*Parameters.Beam.Dcp/Parameters.Beam.tw-3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy);				
102	c(12) = max(Parameters.Demands.LRFD.M_pos)-Parameters.Beam.Mn_pos;				
103	c(13) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;				
104	c(14) = Parameters.Demands.LRFD.fbc_neg(2,:)-Parameters.Beam.Fcrw;				
105	c(15) = Parameters.Demands.LRFD.fbc_neg(1,:)-Parameters.Beam.Fn_neg;				
106	c(16) = Parameters.Demands.LRFD.fbt_neg(1,:)-Parameters.Beam.Fy;				
107	else				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
108	% Constraints for non-compact section				
109	c(1) = max(Parameters.Length*.032) - (Parameters.Beam.d + Parameters.Deck.t);				
110	c(2) = max(Parameters.Length*.027) - Parameters.Beam.d;				
111	c(3) = Parameters.Beam.Dpst/Parameters.Beam.Dt - 0.42;				
112	c(4) = 0.3125 - Parameters.Beam.tw;				
113	c(5) = Parameters.Beam.ind/Parameters.Beam.tw - 150;				
114	c(6) = Parameters.Beam.bf/(2*Parameters.Beam.tf) - 12;				
115	c(7) = Parameters.Beam.ind/6 - Parameters.Beam.bf;				
116	c(8) = 1.1*Parameters.Beam.tw - Parameters.Beam.tf;				
117	c(9) = 3.76*sqrt(Parameters.Beam.E/Parameters.Beam.Fy)-2*Parameters.Beam.Dcp/Parameters.Beam.tw;				
118	c(10) = Parameters.Demands.LRFD.fbc_pos(1,:)-Parameters.Beam.Fn_pos;				
119	c(11) = Parameters.Demands.LRFD.fbt_pos(1,:)-Parameters.Beam.Fn_pos;				
120	c(12) = max(max(Parameters.Demands.LRFD.V))-Parameters.Beam.Vn;				
121	c(13) = Parameters.Demands.LRFD.fbc_neg(2,:)-Parameters.Beam.Fcrw;				
122	c(14) = Parameters.Demands.LRFD.fbc_neg(1,:)-Parameters.Beam.Fn_neg;				
123	c(15) = Parameters.Demands.LRFD.fbt_neg(1,:)-Parameters.Beam.Fy;				
124	end				

Line Num.	Line	Constraint Purpose	AASHTO LRFD Section or Equation	Valid?	If no, why?
125	end				
126	end				
127					
128	ArgOut = c;				
129	end				