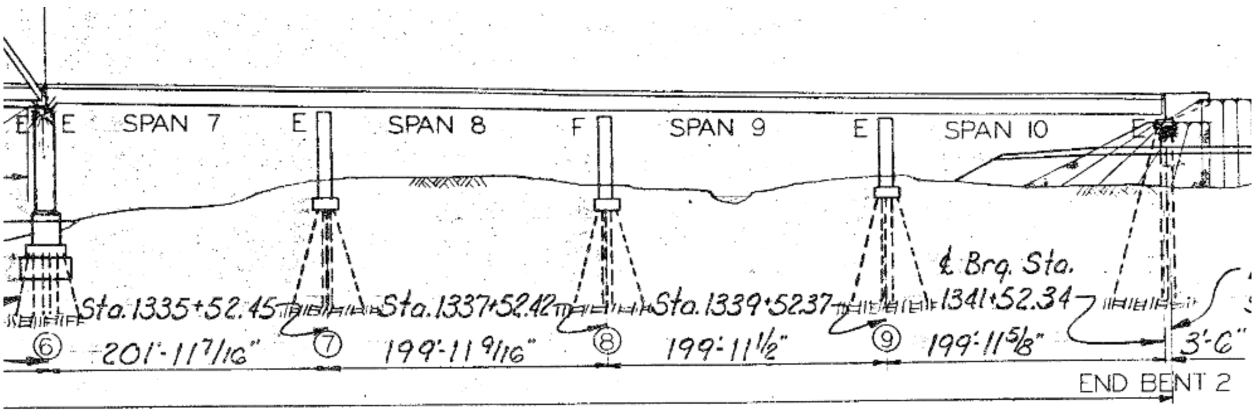
Division of Engineering Research On-Call Services

Task 4: Load Rating of the Combs-Hehl Stringers Under Permit Loads



Prepared by:
James A Swanson
Gian Andrea Rassati
Rachel A Chicchi
Martin A Butler

Prepared for:
The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 135785
Subaward Number UT20480

January 2020

Final Report

U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-2020-2		
4. Title and Subtitle		5. Report Date
Division of Engineering Research On-Call Services **Task 4: Load Rating of the Combs-Hehl Stringers Under Permit Loads**		**January 2020** 6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
James A Swanson, Gian Andrea Rassati, Rachel A Chicchi, and Martin A Butler		
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
Dept Civil and Architectural Engineering and Construction Management, University of Cincinnati, Cincinnati, OH 45221-0071		11. Contract or Grant No. **SJN 135785**
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered
Ohio Department of Transportation **1980 West Broad Street** **Columbus, Ohio 43223**		**Final Report** 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract		
17. Keywords		18. Distribution Statement
		No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**		

Form DOT F 1700.7 (8-72) **Reproduction of completed pages authorized**

Division of Engineering Research On-Call Services

Task 4: Load Rating of the Combs-Hehl Stringers Under Permit Loads

Prepared by:
James A Swanson
Gian Andrea Rassati
Rachel A Chicchi
Martin A Butler

Dept. of Civil and Architectural Engineering
and Construction Management
College of Engineering and Applied Science
University of Cincinnati

January 2020

Prepared in cooperation with the Ohio Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

Acknowledgments

Advice at the beginning of the project from Victor J Hunt and Arthur J Helmicki at the University of Cincinnati is gratefully acknowledged, as is the support of the technical advisory panel throughout the project.

Overview

The Combs-Hehl Bridge is a series of structures over the Ohio River near Cincinnati spanning between Ohio on the east end and Kentucky on the west end. The overall bridge consists of four approach spans on the Kentucky side of the river (spans 1-4), two main truss spans over the river, (spans 5 and 6), and four approach spans on the Ohio side of the river (spans 7-10). The bridge carries interstate route 275 and, as a result, consists of two independent structures: the north bridge carrying westbound traffic and south bridge carrying eastbound traffic. Previous work not described herein addressed rating of the stringers in the Ohio approach spans of the north and south bridges, identified as spans 7-10, under a suite of legal truck loads and emergency vehicles. The scope of work for the project described herein is the rating of the stringers in the Ohio approach spans under a suite of typical permit loads.

The Ohio approach spans of the south bridge consist of five stringers spaced at 8'-2½" spanning 25'-0" between floor beams that are supported by two girders. These girders are spaced at 32'-10" and are supported by piers spaced at 200', for an overall length of 800'. Because of an on-ramp for the westbound traffic on the Ohio side of the river, the north bridge is similar, but not identical, to the south bridge. The Ohio approach spans of the north bridge consist of seven stringers spanning 25'-0" between floor beams that are supported by two girders. The north bridge girders are also supported by piers spaced at 200', for an overall length of 800'. Since the north bridge was designed to accommodate an on-ramp, the width of the bridge changes over its length, with stringer spacing varying from 5'-5½" to 8'-3" and the girder spacing varying from 32'-9" to 49'-6".

The analyses and rating of the approach spans were conducted using three methods. The first method was based on one-dimensional beam-line (1DBL) models to determine demands and traditional hand calculations to determine capacity. The second approach was based on three-dimensional linear and elastic (3DLE) finite element analyses of the bridges to determine demands and traditional hand calculations to determine capacity. The third approach was based on three-dimensional nonlinear and inelastic (3DNI) finite element analyses of the bridges wherein the finite element model itself was able to determine both the demand on, and the capacity of, the stringers. Each of the methods is described in the subsequent sections.

The ratings based on 1DBL analyses were automated and provided relatively conservative results for single permit trucks positioned in many different longitudinal locations on the bridges. The 3DLE analyses and ratings were more rigorous, provided less conservative results than the 1DBL analyses, and were used to investigate the potential of permit trucks acting together with secondary 5C1 legal truck loads in adjacent lanes. Ratings based on the 3DNI analyses were the least conservative and were used to evaluate the strength of the bridges under the most critical truck loads and positions as determined from the 1DBL and 3DLE analyses and ratings.

In each of the rating methods, only the strong-axis moment strength of the stringers was considered. Additional elements such as floor beams, girders, splices, connections, and the deck were not evaluated for strength. Stringers were not evaluated for shear strength, fatigue, axial force, or the possibility of combined axial force and moment. It should be noted that lateral and axial loading could reduce lateral-torsional buckling strength of the stringers. It was also assumed that the deck provides continuous lateral support to the top flanges of the stringers.

1D Beam-Line Modeling

The first method that was used to analyze and rate the stringers was based on a one-dimensional beam-line model. The SAP2000 finite element package was used to generate influence lines for a representative stringer supported by vertically rigid pins and rollers at 25'-0" intervals that represented the locations of the floor beams in the bridges. Stringer J, the center stringer in the south bridge, consisting of W24×76 and W24×55 sections, was selected as representative. Influence lines for strong axis moment were extracted at 10th points and quarter points of each 25'-0" long stringer span over the full 800' length of the approach spans. The influence lines were generated by placing a unit vertical point load at 6" intervals over the full 800' length of the approach spans.

Permanent loads were determined and applied to the influence lines. Permanent loads were distributed evenly to the five stringers and two girders in the south bridge, and to the seven stringers and two girders in the north bridge. Both maximum and minimum load factors were considered for permanent loads; maximum load factors were applied when permanent loads were additive to the effects of truckloads and minimum load factors were applied when permanent loads mitigated the effects of truckloads. No allowance was made for future wearing surface.

The truckloads shown in Table 1 were considered in the analysis. Transverse distribution factors were calculated using both the lever rule and the equations provided in the AASHTO-LRFD specification (2017). Ultimately, a transverse distribution factor of $DF = 0.6345$ lanes per stringer was determined to be critical, which was based on the lever rule with one lane loaded disregarding multiple presence ($MPF = 1.0$). Using this distribution factor, permit loads were applied to the influence lines by moving the load pattern in 1' intervals over the entire 800' length of the bridge both forwards and backwards. Individual axle loads that acted to mitigate the overall moment were not included. In the 1DBL analyses, the permit loads were applied individually, in the absence of secondary vehicles, and lane loads were not considered. The analyses were conducted using dynamic load allowances of 33% and 3% (i.e. impact factors of 1.33 and 1.03, respectively) were applied to the axle loads of all trucks. Rating factors were computed at the operating level using load factor of 1.30 for live load plus impact ($LL + IM$).

Table 1: Permit Truck Configurations Considered During 1DBL Analyses and Rating

• 8 Axle	• 13 Axle Short
• 10 Axle	• 13 Axle Long
• 12 Axle	• 20 Axle

The moment capacity that was used for rating purposes was based on Appendix A6 of the AASHTO-LRFD specification (2017). The top flanges of the stringers are continuously laterally supported by the concrete deck and haunches while the bottom flanges are laterally supported at 25'-0" intervals at their connections to the floor beams. Yielding / plastic hinging was the critical mode of failure in positive moment regions while lateral-torsional buckling (LTB) was the critical mode of failure in negative moment regions. The strength associated with plastic hinging is well established and is taken as the product of the plastic section modulus and the yield strength of the steel. The strength model used for LTB is based on an eigensolution of the buckling problem and includes a moment gradient modifier, C_b, to account for non-uniform distributions of moment over the unbraced length.

A refined moment gradient modifier formulation based on work by Yura and Helwig was used in both the 1DBL and 3DLE analyses and ratings (Yura and Helwig, 2010; Ziemian, 2010; Swanson et. al., 2019). Use of this refined formulation, however, required that C_b be calculated using concurrent moments from diagrams instead of envelopes (AASHTO 2017). As a result, a unique value of C_b was computed for every unbraced span, for every permit truck considered, and for every truck position considered.

The governing rating factor for each permit truck loading is shown in Table 2. The 20 axle permit loading was found to be most critical and the 12 axle permit truck was found to be second most critical permit load. Both of these permit loads resulted in critical load ratings in the stringers under negative moment at interior floor-beam support locations.

Table 2: Rating Factors based on 1D Beam-Line Analysis Approach

	***IM* = 1.33**	***IM* = 1.03**
8 Axle Permit Truck Alone:	*RF* = 1.13	*RF* = 1.58
10 Axle Permit Truck Alone:	*RF* = 1.15	*RF* = 1.52
12 Axle Permit Truck Alone:	*RF* = 1.09	*RF* = 1.41
13 Axle Short Permit Truck Alone:	*RF* = 1.20	*RF* = 1.56
13 Axle Long Permit Truck Alone:	*RF* = 1.13	*RF* = 1.45
20 Axle Permit Truck Alone:	*RF* = 1.00	*RF* = 1.30

All ratings in this table based on γ_{LL} = 1.30, *DF* = 0.6345 and *MPF* = 1.00

3D Linear Elastic Modeling

Three dimensional linear-elastic (3DLE) finite element models of the bridges were created using the SAP2000 software. The models included main girders, floor beams, and stringers, all modeled using beam elements, as well as the deck, which was modeled using shell elements. The weight of the barrier walls was included in the model but the barrier stiffness was not included. The girders were supported at the pier locations every 200'. Modeling efforts focused on the south bridge but results were corroborated using a model of the north bridge. A view of the unloaded model with the deck elements hidden is shown in Figure 1.

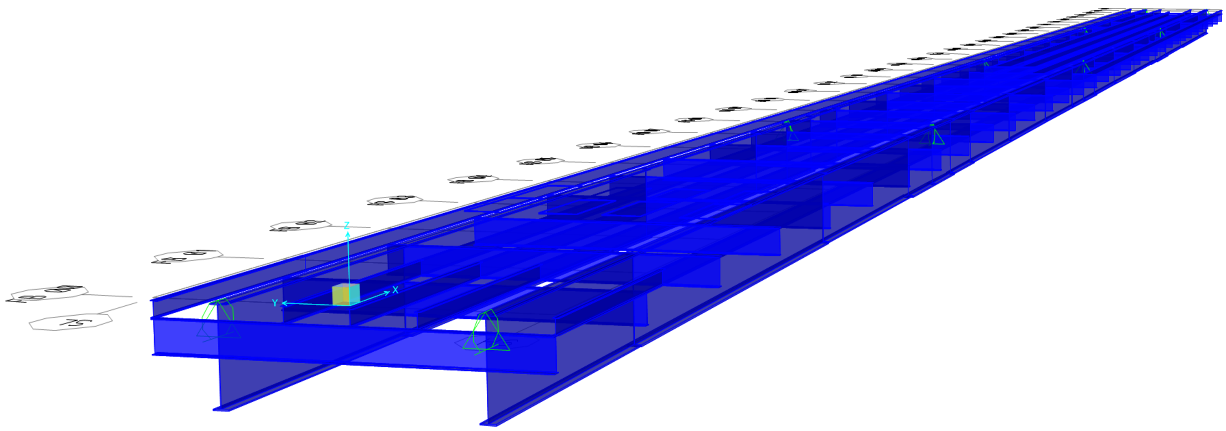


Figure 1: 3D Linear Elastic Model of the South Bridge

The model was loaded with (a) a 20 axle permit truck in one lane with a 5C1 truck in an adjacent lane, and (b) a 12 axle permit truck in one lane with a 5C1 truck in an adjacent lane, adhering to the lane definitions in the AASHTO-LRFD specification (2017). In both cases, a dynamic load allowance of 33% (i.e. an impact factor of 1.33) was applied to the axle loads of all trucks, and rating factors were computed at the operating level using a load factor of 1.30.

The longitudinal positions of the permit trucks were based on critical positions determined during the 1DBL analyses and ratings, and confirmed with 3DBL analyses of the bridge under the permit loading alone. The critical lateral positions were determined during preliminary 3DLE analysis of the bridge under the permit load alone with the lateral position varied in 3’ increments over the full width of the bridge. The 5C1 truck was then added in an adjacent lane such that the 5C1 truck faced in the same direction as the permit truck and its longitudinal position was varied starting with the rear axles of both trucks at the same longitudinal position and ending with the front axles of both trucks at the same longitudinal position, moving the 5C1 truck at 1’ increments.

Strength calculations used to rate the stringers in the 3DLE analyses were identical to those used with the 1DBL ratings, based on C_b values computed using the modified Yura and Helwig approach described earlier. A critical rating factor of $RF = 2.30$ was found in the edge stringers due to negative moment at station 200’ (Floor Beam 8 / Pier 7 on the original plans) resulting from the 20 axle permit truck positioned near the parapet with a 5C1 truck positioned in the adjacent lane. Similarly, a rating factor of $RF = 3.14$ was found in the edge stringers due to negative moment at station 200’ resulting from the 12 axle permit truck positioned near the parapet with a 5C1 truck positioned in the adjacent lane.

A critical rating factor of $RF = 2.55$ was found in the center stringer due to negative moment at station 200’ resulting from the 20 axle permit truck centered on the bridge with a 5C1 truck position in the adjacent lane. Finally, a rating factor of $RF = 2.58$ was found in the center stringer due to negative moment at station 200’ resulting from the 12 axle permit truck positioned 3’ off center in one direction with a 5C1 truck position in the adjacent lane in the opposite direction.

It is postulated that the less conservative rating factors that were calculated using the 3DLE method are reflective of the three-dimensional behavior of the bridge that is captured in the 3DLE analyses but not in the 1DBL analyses. In the 1DBL analyses, the stringers are supported at 25’ 0” intervals by supports that are infinitely rigid vertically. In the 3DLE analyses, however, the stringers are instead supported by floor beams that deflect vertically as the supporting girders deflect. The girders, with their spans of 200’, are the primary load carrying elements in bridge and their deflection affects the load distribution within the stringers in a way that reduces the moment demand on the stringers.

3D Nonlinear Inelastic Modeling

Three dimensional nonlinear-inelastic (3DNI) finite element models of the bridges were created using the ABAQUS software. The models included the main girders, floor beams, stringers and deck, all modeled using shell elements. Transverse members between the stringers at the floor beam locations were not included in the model; their presence would likely have increased the strength of the stringers. The weight of the barrier walls was included in the model but the barrier stiffness was not included. The girders were supported every 200’ at the pier locations. Modeling efforts focused on the south bridge but results were corroborated using a model of the north bridge. Because of the rigor of analyzing the 3DNI models, most analyses were performed on 200’ long or 400’ long segments of the bridges, often spans 7 and 8. A view of the unloaded 3DNI model of the south bridge with the deck elements hidden is shown in Figure 2 and a view of the unloaded 3DNI model of the north bridge with the deck elements hidden is shown in Figure 3.

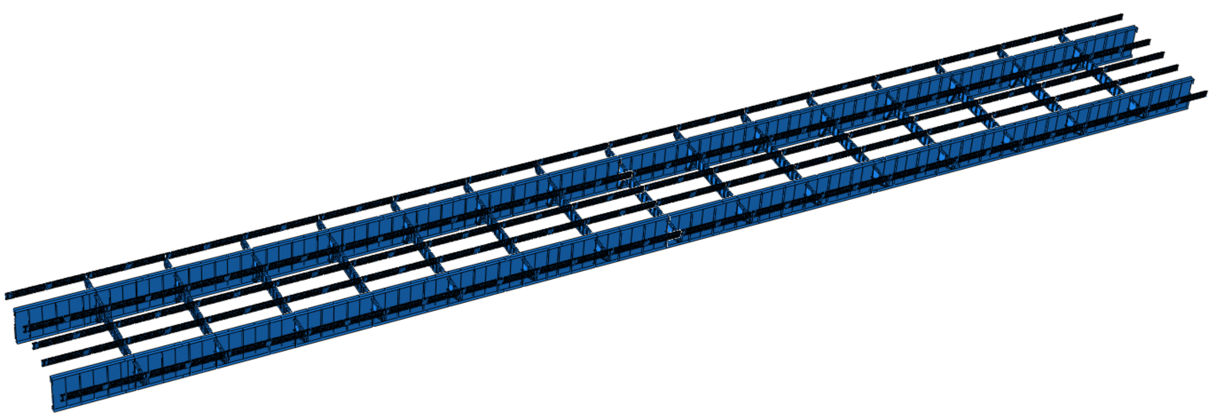


Figure 2: View of the 3DNI Model of the South Bridge

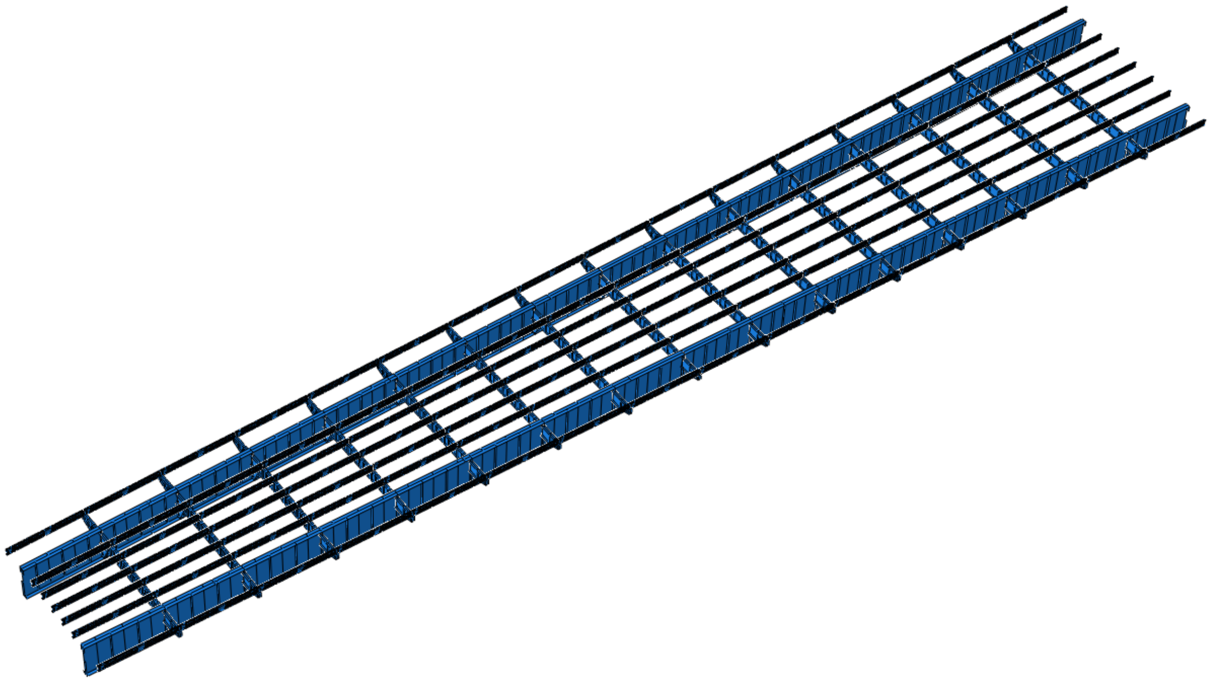


Figure 3: View of the 3DNI Model of the North Bridge

The goal of the 3DNI modeling was to confirm results from the 3DLE analyses and ratings for critical truck configurations and positions. Because the 3DNI models were used for both the determination of the moments in the stringers and for determination of the stringer strengths, they were naturally far more detailed than the 3DLE models. The 3DNI models were based on shell elements and included details such as residual stresses and initial geometric imperfections that were necessary to capture buckling failures effectively. Additionally, contact and separation behavior was defined between the deck and top flanges of the stringers and analytical constraints were defined to represent connections between the stringers and floor beams and between the floor beams and main girders. Additional details regarding the construction and validation of the 3DNI models can be found in Swanson et al. (2019).

The 3DNI bridge models were loaded using uniform pressures for permanent loads other than self-weight, all including appropriate load factors, and point loads representing the wheel loads. The magnitude of the wheel loads was then incrementally increased until a failure in the model was observed as an analytical instability (failure of the analysis to converge to a solution during a given increment). Based on 1DBL and 3DLE analyses and ratings, an analysis with a 20 axle permit truck in one lane and a 5C1 truck in an adjacent lane was conducted.

The models were initially analyzed with nonlinear material properties for all steel and concrete. The first analysis resulted in an observed failure in the main girders. Since the girders were not the focus of the study, however, the girder elements were redefined with elastic material properties to preclude girder yielding and the model was analyzed again. The second analysis resulted in an observed failure in Floor Beam #8. Since the floor beams were not the focus of the study, the floor beam elements were redefined with elastic material properties to preclude yielding of these elements, and the model was analyzed a third time. The third analysis resulted in the application of approximately 200% of the factored wheel loads including impact without an observed failure in the stringers.

Conclusions:

Based on the 1D Beam Line analysis and rating, it was determined that the minimum operating rating factor for the stringers was found to be 1.00 due to the 20 axle permit truck on the bridge alone. The next smallest operating rating factor for the stringers was found to be 1.09 due to the 12 axle permit truck on the bridge alone. Based on the 3D Linear Elastic modeling and rating, a minimum operating rating factor of 2.30 was found due to a 20 axle permit truck loading with a 5C1 truck in an adjacent lane. Based on the 3D Nonlinear Inelastic modeling and rating, no failures in the stringers were observed under the full factored dead load and 200% of the factors weight of a 20 axle permit truck in one lane and a 5C1 truck in an adjacent lane. All of these rating factors were computed using a dynamic load allowance of 33%.

References:

AASHTO (2017), AASHTO LRFD Bridge Design Specifications, 8th Edition, American Association of State Highway and Transportation Officials, Washington DC, Sep 2017

Swanson, J.A., Rassati, G.A., Chicchi, R.A., and Butler, M.A. (2019), Division of Engineering Research On-Call Services - Task 2: Rating of the Stringer System of the Approach Spans of the Combs-Hehl Bridge, submitted to the Ohio Department of Transportation, Jan 2019

Yura, J.A. and Helwig, T.A. (2010), "Buckling of Beams with Inflection Points," Proceedings, Annual Stability Conference, Orlando, FL, North American Steel Construction Conference, SSRC.

Ziemian, R. D. (2010), Guide to Stability Design Criteria for Metal Structures, Sixth Edition, Structural Stability Research Council, John Wiley and Sons, Inc., New York, NY.