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Experimental study of stringer lateral torsional resistance using a grillage system

C. Shawn Sun [1], Daniel G. Linzell [2], Jay A. Puckett [3], Ahmed Rageh [4], Oluwatobi Babarinde [5], Dinesha Kuruppuarachchi [6]

Abstract
This paper summarizes an extensive experimental program examining lateral torsional buckling resistance of two-span, continuous, steel beams in a grillage system. The grillage had three beam lines, an interior transverse support and transverse diaphragms at its end supports. The tests, sponsored by the Louisiana Transportation Research Center, were as part of a research project aimed at developing more realistic moment gradient factors (C_b) than those currently used in Louisiana to load rate steel truss and girder bridges whose floor systems consist of continuous stringers supported by floorbeams. Current practice results in ratings that are conservatively controlled by the stringers and, in many cases, necessitate posting a bridge that would otherwise be able to continue normal operations. Nearly 50 elastic tests of the grillage were completed. The tests encompassed a variety of unbraced lengths and support conditions with steel diaphragms or timber struts acting as bracing members. The interior beam in the grillage was loaded orthogonal to its strong axis at the middle of one or both spans using a flexible spreader beam system that prevented development of follower forces. Test results demonstrated that minimal bracing could provide adequate lateral torsional buckling resistance and justified use of a higher moment gradient factor than that currently used in Louisiana.

1. Introduction

1.1 Research Need

Some of the Louisiana's bridges built in the 1950s and 1960s used two-girder or truss systems, in which floorbeams are carried by main members and continuous (spliced) stringers are supported by the floorbeams (Sun et al. 2021). The main members are either two edge (fascia) girders or trusses. When the continuous stringers are load-rated using AASHTOWare Bridge Rating™

[1] Assistant Professor, Louisiana Tech University, <shawn@latech.edu>
[2] Associate Dean and Professor, University of Nebraska – Lincoln, <dlinzell@unl.edu>
[3] Director and Professor, University of Nebraska – Lincoln, <jay.puckett@unl.edu>
[4] Project Engineer, SDR Engineering, <a.eissa.rageh@gmail.com>
[5] Graduate Research Assistant, Louisiana Tech University, <ofb001@latech.edu>
[6] Graduate Research Assistant, Louisiana Tech University, <dku003@latech.edu>

analysis software, C_b is calculated in accordance with the *AASHTO LRFD Bridge Design Specifications* (AASHTO 2020), which does not attempt to account for bracing effects that could be provided by a non-composite deck. As a result, it underestimates the stringer's lateral torsional buckling (LTB) resistance and may necessitate posting a bridge. Therefore, the Louisiana Transportation Research Center funded a research project to develop more realistic moment-gradient factors than those currently used in Louisiana to load rate continuous stringers. As part of the research project, an experimental study was conducted to evaluate the LTB resistance and C_b for continuous stringers. This paper presents the first set of tests within a reduced-scale grillage prior to placement of a non-composite concrete deck.

1.2 Moment Gradient Factor

Several specifications and codes use gradient factors to account for variations in moment along the length of a flexural member, including the *AISC Steel Construction Manual* (AISC 2017)*, the AASHTO LRFD Bridge Design Specifications*, the *Canadian Highway Bridge Design Code* (CSA 2014), the *Australian Steel Code* (SA 1998), the *British Standards Structural Use of Steelwork in Building* (BSI 2000), and the *Japanese Standard Specifications for Steel and Composite Structures* (JSCE 2007). A brief summary of relevant activities relevant to the current study follows.

The *AISC Steel Construction Manual* provides the C_b for nonuniform moment diagrams primarily based on the research work by Kirby and Nethercot (1979) with slight modifications. C_b is determined by Eq. 1:

$$C_b = \frac{12.5M_{max}}{2.5M_{max}+3M_A+4M_B+3M_C} \qquad (1)$$

where: M_{max} is the absolute value of maximum moment in the unbraced segment; M_A is the absolute value of moment at quarter point of the unbraced segment; M_B is the absolute value of moment at center of the unbraced segment; and M_C is the absolute value of moment at three-quarter point of the unbraced segment.

In accordance with the AASHTO LRFD Bridge Design Specifications, C_b can be determined using Eq. 2 as follows:

$$C_b = 1.75 - 1.05\left(\frac{f_1}{f_2}\right) + 0.3\left(\frac{f_1}{f_2}\right)^2 \le 2.3 \qquad (2)$$

where: f_1 is the stress without consideration of lateral bending at the brace point opposite to the one corresponding to f_2, calculated as the intercept of the most critical assumed linear stress variation passing through f_2 and either f_{mid} or f_0, whichever produces the smaller value of C_b.

As shown in Eq. 3, Helwig et al. (1997) suggested multiplying the original equation for C_b from Kirby and Nethercot by the terms $1.4^{2y/h}$ to account for the effects of load height within the cross-section and by R to account for effects of I-section monosymmetry and reverse curvature bending in prismatic members.

$$C_b = \frac{12.5M_{max}}{2.5M_{max}+3M_A+4M_B+3M_c}\left(1.4^{2y/h}\right)R \qquad (3)$$

where: y is the distance from the depth of the cross section to the point of the load application, which is taken as negative for downward loads applied above mid-depth and positive for downward loads applied below mid-depth; h is the distance between the compression and tension flange centroids; and R is 1.0 for beams with single-curvature bending. For reverse-curvature bending, R can be determined by Eq. 4:

$$R = 0.5 + 2\left(\frac{I_{y\,Top}}{I_y}\right)^2 \qquad (4)$$

where: $I_{y\ \mathrm{Top}}$ is the moment of inertia of the top flange about an axis in the plane of the web; and I_y is the moment of inertia of the entire section about an axis in the plane of the web.

Wong and Driver (2010) reviewed several approaches and recommended the following quarter-point equation for use with doubly symmetric I-shaped members as provided in Eq. 5. The definitions of various moments are the same as the *AISC Steel Construction Manual*.

$$C_b = \frac{4M_{max}}{\sqrt{{M_{max}}^2+4{M_A}^2+7{M_B}^2+4{M_c}^2}} \qquad (5)$$

Yura and Helwig (2010) studied the stringers subject to reverse curvature bending with one of the flanges continuously braced laterally by closely spaced joists and/or light gauge decking normally used for roofing or flooring systems. For gravity loaded, rolled I–section stringers with the top flange laterally restrained, Eq. 6 is applicable:

$$C_b = 3.0 - \frac{2}{3}\left(\frac{M_1}{M_0}\right) - \frac{8}{3}\left[\frac{M_{CL}}{(M_1+M_0)^*}\right] \qquad (6)$$

where: M_0 is the moment at the end of the unbraced length that gives the largest compressive stress in the bottom flange; M_1 is the moment at other end of the unbraced length; M_{CL} is the moment at the middle of the unbraced length; and $(M_0 + M_1)^* = M_0$, if M_1 is positive, causing tension on the bottom flange.

2. Experimental Program

This paper summarizes an extensive experimental program examining LTB resistance of two-span, continuous, steel beams in a grillage system. The grillage had three beam lines, an interior transverse support, and transverse diaphragms at its end supports. Nearly 50 elastic tests of the grillage were completed. The tests encompassed a variety of unbraced lengths and support conditions with steel diaphragms or timber struts acting as bracing members. The interior beam in the grillage was loaded orthogonal to its strong axis at the middle of one or both spans using a flexible spreader beam system that prevented development of follower forces.

2.1 Test Setup

The test frame was designed to address critical parameters from a group of representative bridges, including span, spacing, and size of the stringers, material properties, and support conditions. The basic setup was a grillage system that accommodated a variety of bracing configurations and stringer-to-floorbeam relative stiffness and connection fixity conditions. The grillage system included three lines of 50-ft long W16x31 stringers, one 25-ft long W24x68 floorbeam, and C12x20 end diagrams bolted to the stringers. Figs. 1 and 2 show the framing plan and a section of the grillage at the floorbeam, respectively. The grillage was a two-span structure having 24-ft spans between the centerlines of bearings. Stiff supports underneath the floorbeam at different locations helped create rigid or flexible conditions.

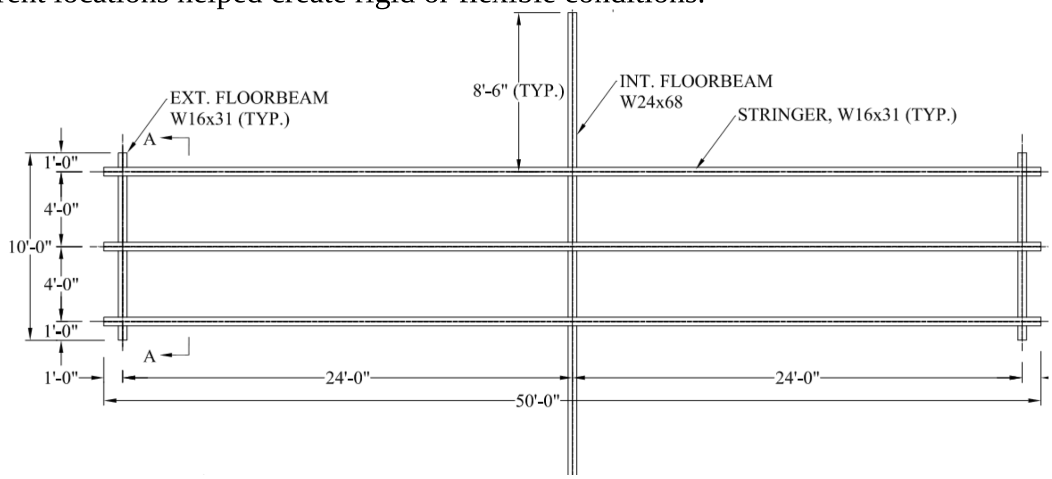

Fig. 1. Grillage system framing plan

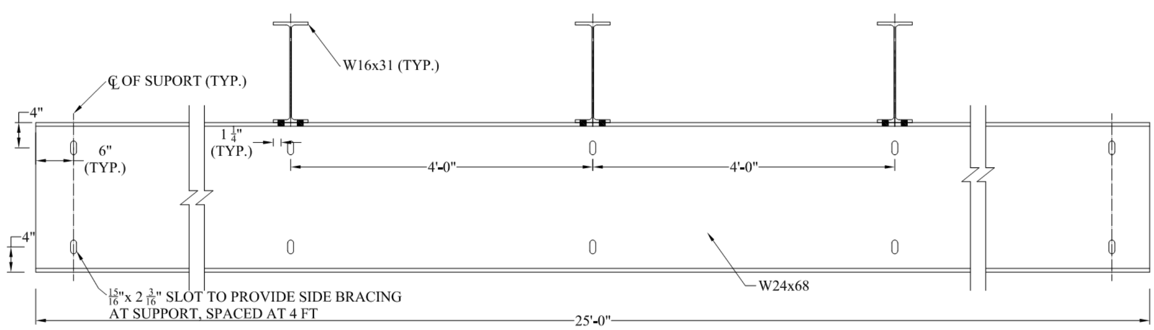

Fig. 2. Grillage system section at floorbeam

2.2 Test Matrix

Table 1 provides the complete test matrix, including: groupings; corresponding configurations (i.e., test setups); stringer support conditions (i.e., floorbeam flexural stiffness); loading and bracing conditions; and test run identification numbers. Testing is categorized into three general groups as listed in Table 1. For both balanced and unbalanced loading conditions, a concentrated force was applied at midspan of one or both spans. When an unbalanced load was applied, the unloaded stringer end was tied down to avoid possible uplift. The grillage system was repeatedly used in all tests.

Group I consists of test setup Nos. 1, 1A, 1B, and 1C, in which grillage system stringer top flanges were unbraced (Fig. 3). Either a rigid or flexible interior floorbeam was provided. The stringer bottom flanges were either unbolted or bolted at the floorbeam. When bolted, 7/8 in. diameter high-strength bolts were used. Balanced and unbalanced loads were applied. This group includes Tests 1 to 8 and serves as a baseline for comparison to other groups.

Group II consists of setup Nos. 1' and 1'A, in which the grillage system stringers were braced by intermediate steel diaphragms at various locations, including at the interior support and *L*/2, *L*/8, *L*/4, and 3*L*/8 away from the interior support, where *L* is the span length. The diaphragms were bolted to the stringers and rigid interior support was provided beneath the stringers by supporting the floorbeam on the laboratory strong floor with steel plates. The stringer bottom flanges were either unbolted or bolted at the floorbeam. Balanced and unbalanced loads were applied. This group includes Tests 9 to 28. Fig. 4 shows an example of Group II setup.

Group III consists of test setup Nos. 2, 2A, 2B, and 2C, in which the grillage system stringer top flanges were laterally braced using timber ties (4" x 4") connected to the flanges using C-clamps (Fig. 5). These setups were intended to represent a transition of bracing conditions before a non-composite concrete deck was placed and allowed for a wide range of bracing conditions to be efficiently studied. Either a rigid or flexible interior floorbeam was provided. The stringer bottom flanges were either unbolted or bolted at the floorbeam. Balanced loads were applied. This group includes Tests 29 to 44.

Fig. 3. Example Group I setup

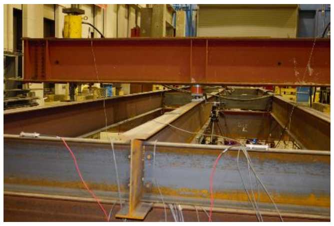

Fig. 4. Example Group II setup

Fig. 5. Example Group III setup

Table 1: Test matrix

Group	Test setup	Description of boundary conditions			Load condition	Test Run #
		Interior support at center stringer	**Top flange of stringer**	**Bottom flange of stringer**		
I	No. 1	Rigid	Unbraced	Unbraced	1 point load	1
					2 point loads	2
	No. 1A			Braced laterally by bolts	1 point load	3
					2 point loads	4
	No. 1B	Flexible		Unbraced	1 point load	5
					2 point loads	6
	No. 1C			Braced laterally by bolts	1 point load	7
					2 point loads	8
II	No. 1'	Rigid	Diaphragms @ Int. Support	Unbraced	1 point load	9
					2 point loads	10
			Diaphragms @ L/2		1 point load	11
					2 point loads	12
			Diaphragms @ L/8 from Int. Support		1 point load	13
					2 point loads	14
			Diaphragms @ L/4 from Int. Support		1 point load	15
					2 point loads	16
			Diaphragms @ 3L/8 form Int. Support		1 point load	17
					2 point loads	18
	No. 1'A	Rigid	Diaphragms @ Int. Support	Braced laterally by bolts	1 point load	19
					2 point loads	20
			Diaphragms @ L/2		1 point load	21
					2 point loads	22
			Diaphragms @ L/8 from Int. Support		1 point load	23
					2 point loads	24
			Diaphragms @ L/4 from Int. Support		1 point load	25
					2 point loads	26
			Diaphragms @ 3L/8 form Int. Support		1 point load	27
					2 point loads	28
III	No. 2	Rigid	Timber strut @ L/2, TF	Unbraced	2 point loads	29
			Timber strut @ L/3, TF		2 point loads	30
			TS @ L/4, L/2, L, L/2, L/4		2 point loads	30'
			Timber strut @ L/4, TF		2 point loads	31
			Timber strut @ L/5, TF		2 point loads	32
	No. 2A		Timber strut @ L/2, TF	Braced laterally by bolts	2 point loads	33
			Timber strut @ L/3, TF		2 point loads	34
			TS @ L/4, L/2, L, L/2, L/4		2 point loads	34'
			Timber strut @ L/4, TF		2 point loads	35
			Timber strut @ L/5, TF		2 point loads	36
			TS @ L/8, L/4, L/2, L, L/8, L/4, L/2		2 point loads	36'
	No. 2B	Flexible	Timber strut @ L/2, TF	Unbraced	2 point loads	37
			Timber strut @ L/3, TF		2 point loads	38
			Timber strut @ L/4, TF		2 point loads	39
			Timber strut @ L/5, TF		2 point loads	40
	No. 2C		Timber strut @ L/2, TF	Braced laterally by bolts	2 point loads	41
			Timber strut @ L/3, TF		2 point loads	42
			Timber strut @ L/4, TF		2 point loads	43
			Timber strut @ L/5, TF		2 point loads	44

2.3 Instrumentation

Load and pressure cells, strain gauges and LVDTs measured applied forces and grillage response. Instrument locations are detailed in Fig. 6. Strain gauges were placed at multiple sections on the interior stringer and critical exterior stringer sections to capture effects due to primary, lateral and weak axis bending moments, torsion and axial loads. Gauges were installed at both top and bottom flanges of the stringers. LVDTs were installed at midspan of the interior stringer of both spans and were oriented to capture vertical or lateral deflections. Load and pressure cells were provided at the spreader beams used to track applied forces to the grillage. Testing results are commonly reported at four critical locations herein. Those sections are presented in Table 2.

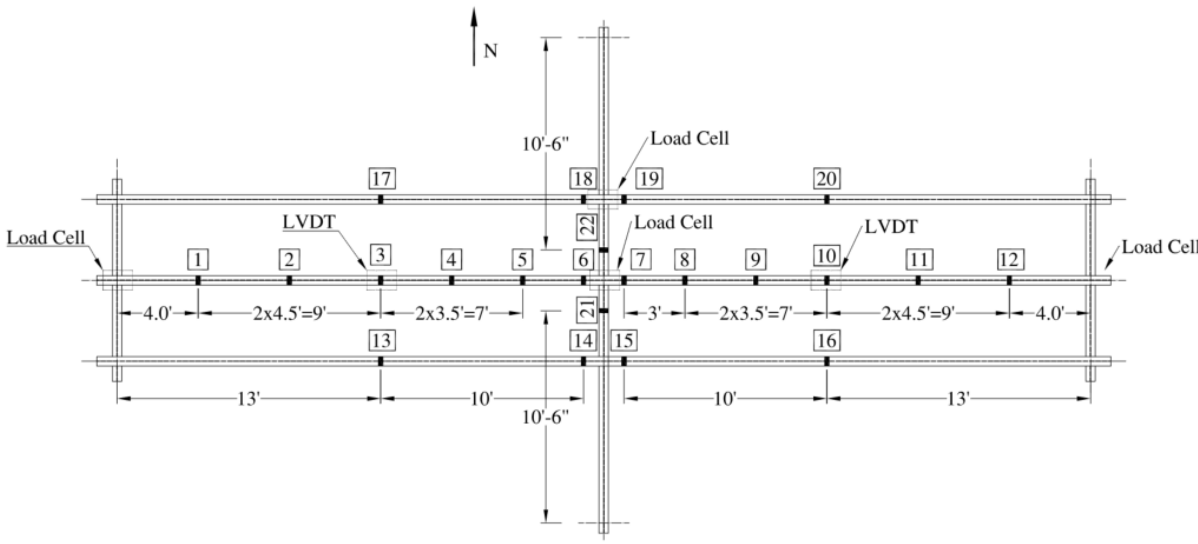

Fig. 6. Instrumentation Plan View

Table 2: Four critical locations

Location	Description
3	Midspan max. +M when loaded at Loc. 3 Midspan -M when loaded at Loc. 10
6	Critical -M location adjacent to floorbeam
7	Critical -M location adjacent to floorbeam
10	Midspan max. +M when loaded at Loc. 10 Midspan -M when loaded at Loc. 3

3. Test Results

The following sections describe test results for each group. Representative results are presented by examining load verses stringer vertical and lateral deflections, and load verses stringer strains at the representative sections. Axial, primary and out-of-plane bending, and warping torsion normal stress components are also provided at individual sections.

3.1 Group I Tests

As indicated in Table 1, Group I tests were of the grillage system with no intermediate stringer bracing. Fig. 7 demonstrates LTB of the interior stringer observed during the tests. Test Runs #1, 3, 5 and 7 results are presented for discussion purposes. They accounted for a rigid or flexible interior floorbeam and the stringer bottom flanges were either unbolted or bolted at the floorbeam. Load-lateral deflection plots in Fig. 8 show that Test Run #3 provided the largest lateral stiffness because stringer bottom flanges were bolted to the floorbeam and the floorbeam was stiff (i.e., supported underneath each stringer). Test Run #1 provided the lowest lateral stiffness because stringer bottom flanges were not connected to the floorbeam. Test Runs #5 and 7, both of which had flexible interior supports, exhibited lateral stiffness between Test Runs #1 and 3. Test Run #7 provided slightly higher lateral stiffness than Test Run #5 because stringer bottom flanges were bolted to the floorbeam.

Fig. 7. LTB of the interior stringer, Test Run #3

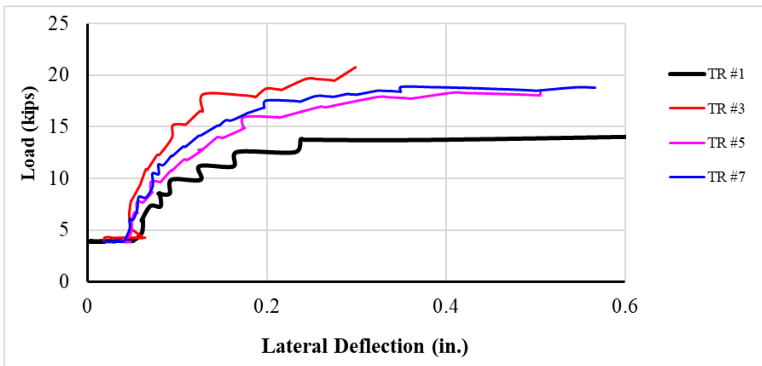

Fig. 8. Load-lateral deflection plots, Test Runs #1, 3, 5, and 7

Figs. 9 and 10 present load-strain plots for the four tests at Loc. 3 TN (top north) and TS (top south) (see Fig. 6). Test Run (TR) #1 exhibited comparable strains to the other three test runs until it reached its peak load, which, again, was lower than that for the other test runs. Note that LTB is clearly evident in three of the four tests.

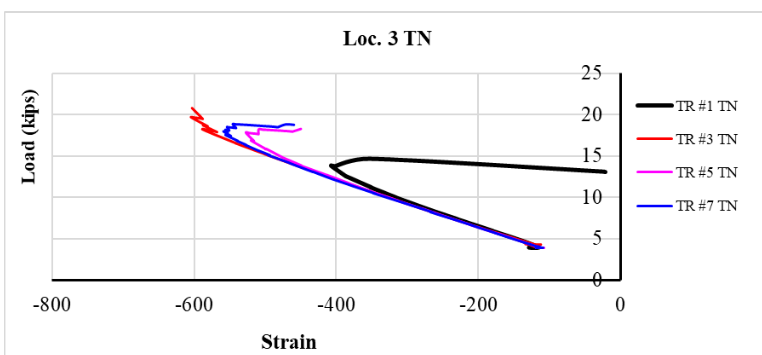

Fig. 9. Load-strain plots at Loc. 3 TN

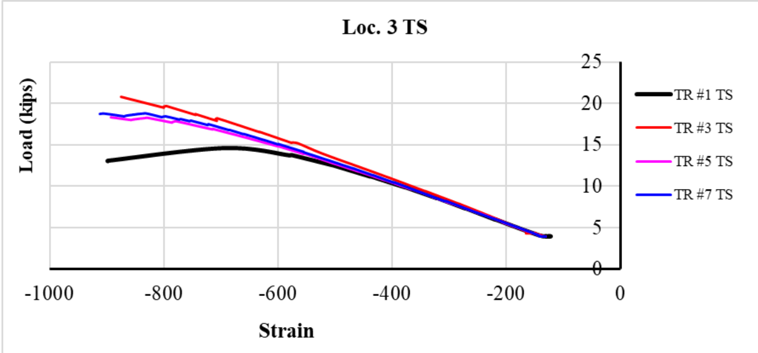

Fig. 10. Load-strain plots at Loc. 3 TS

To further assess behavior at a typical section, strains were converted to stresses and values were decoupled to capture axial, primary and out-of-plane bending, and warping torsion normal stress components (Fig. 11). For illustration purposes, Fig. 12 shows stress components at Loc. 3 TN in Test Run #1. LTB clearly occurred at the peak load, as witnessed by the calculated out-of-plane bending and warping torsion stresses.

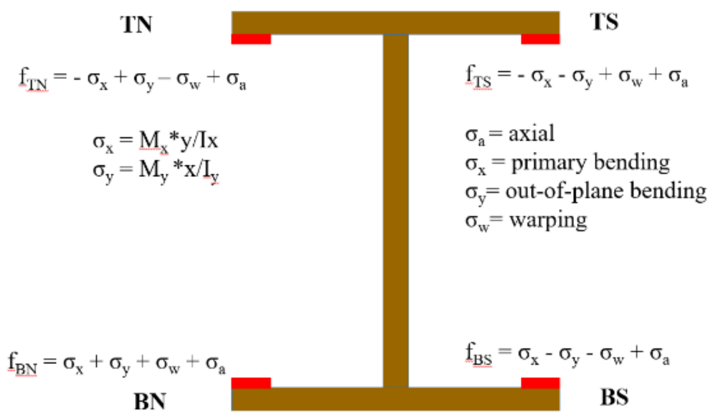

Fig. 11. Stress components

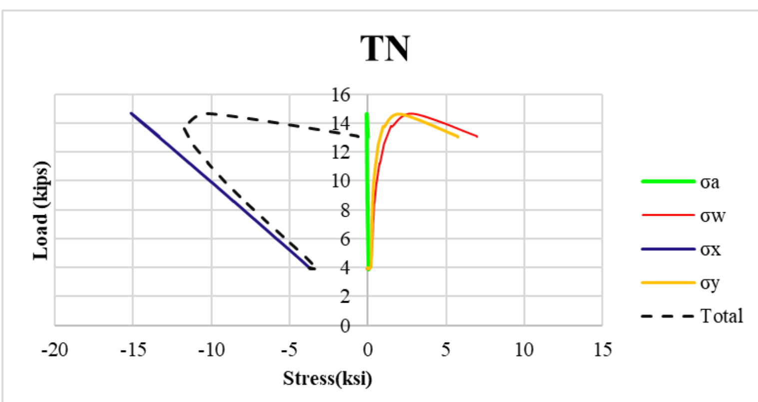

Fig. 12. Stress components, Loc. 3 TN, Test Run #1

3.2 Group II Test Results – Intermediate Bracing by Diaphragms

Rigid interior supports were provided for Group II test setups, while stringer bottom flanges were either unbraced or braced at the floorbeam by the use of 7/8 in. diameter high-strength bolts. Intermediate steel diaphragms were installed at various locations to study their effect on LTB. Fig. 13 illustrates measured buckling load capacities for unbraced lengths between 12 and 24 ft. The interior stringer was loaded at midspan of one or both spans and was bolted to the floorbeam, representing a continuous stringer subjected to a single or double tandems in a bridge. As expected, larger unbraced lengths corresponded to reduced buckling loads.

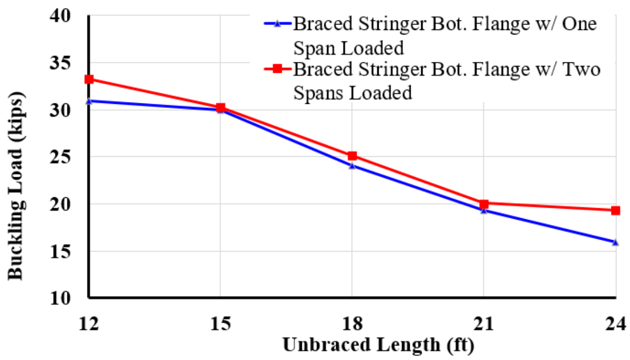

Fig. 13. Intermediate steel diaphragm effect on LTB, stringer bolted to floorbeam

3.3 Group III Test Results – Intermediate Bracing Using Timber Ties

As indicated in Table 1, Group III tests were of the grillage system braced by timber ties. These ties (4”x4”) were installed on the stringer top flanges using C-clamps. Table 3 provides descriptions of Test Run #2 and #29 to 32, which were subjected to concentrated loads at midspan of both spans. Fig. 14 plots load-lateral deflection variations and Fig. 15 plots load-strain variations at Loc. 3 TN. Beneficial effects of minimal lateral bracing were clearly demonstrated as use of a pair of timber ties at midspan (TR #29) nearly doubled the capacity when compared to the baseline, unbraced test (TR #2). Midspan bracing was also shown to be more effective than bracing using ties spaced at L/3 (TR #30). Bracing effects for ties spaced at L/4 and L/5 (TRs #31 and #32) were nearly identical and only nominally improved capacity over that observed for TR #29.

Table 3: Descriptions of Test Run Nos. 2, and 29 to 32 that are subject to loading at both spans

Test Run No.	Description of boundary conditions			
	Floorbeam relative stiffness	Stringer top flange bracing		Stinger bottom flange bracing
2	Rigid	Unbraced		Unbraced
29	Rigid	Timber ties (4”x4”), connected using C-clamps	Spaced at L/2	Unbraced
30	Rigid		Spaced at L/3	Unbraced
31	Rigid		Spaced at L/4	Unbraced
32	Rigid		Spaced at L/5	Unbraced

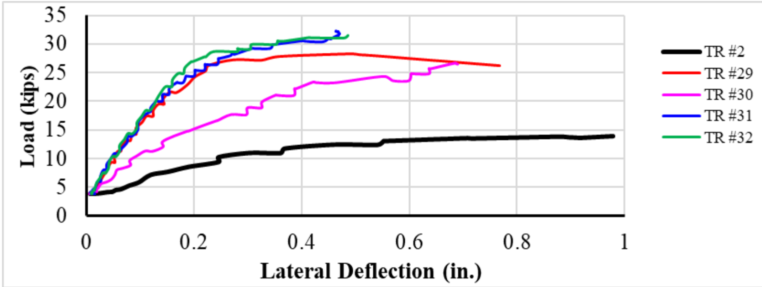

Fig. 14. Load-lateral deflection plots

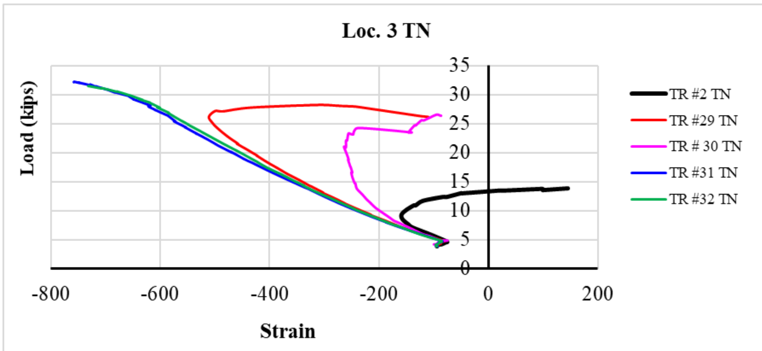

Fig. 15. Load-strain plots at Loc. 3 TN

Bracing effects provided by timber ties was further evaluated for a number of test runs in Fig. 16, which provides buckling loads as a function of tie spacings. Group III test results show that the LTB resistance can be increased significantly using minimal lateral stiffness provided by 4 in. by 4 in. timber ties and C-clamps. For example, buckling load increased by approximately 70% for all tests when timber ties were provided at midspan. These results indicate that the bracing effect of timber struts, which provide minimal lateral stiffness, lend credence to potential benefits of noncomposite decks can provide to LTB resistance and demonstrate that larger moment gradient factors than those assumed during load rating can result.

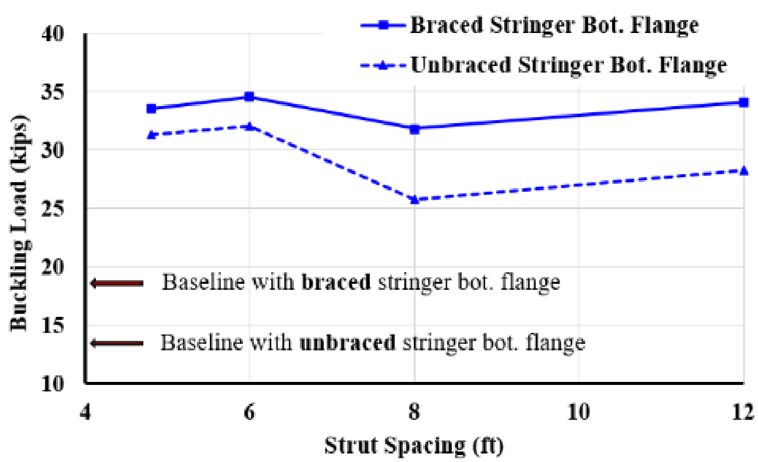

Fig. 16. Bracing effect of timber ties with rigid interior support

4. Conclusions

A series tests encompassing two load cases and a variety of unbraced lengths and support conditions with steel diaphragms or timber struts acting as bracing members were completed. This provides a robust database to be curated elsewhere. Test results demonstrated that minimal bracing could provide adequate lateral torsional buckling resistance and appeared to justify use of a higher moment gradient factor than what is typically used in Louisiana to account for bracing effects of non-composite concrete decks. These tests also served as an important basis for subsequent tests that included a non-composite concrete deck that is typical of the in-service condition.

Acknowledgments

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