University Transportation Research Center - Region 2

Final Report

Effect of Implementing Lean-On Bracing in Skewed Steel I-Girder Bridges

Performing Organization: The College of New Jersey

September 2016

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

Technology Transfer

UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

Project No(s):
UTRC/RF Grant No: 49198-21-27

Project Date: September 2016

Project Title: Effect of Implementing Lean-On Bracing in Skewed Steel I-Girder Bridges

Project's Website:
http://www.utrc2.org/research/projects/improving-cross%E2%80%90frame-design

Principal Investigator(s):
Dr. Andrew J. Bechtel
Associate Professor
Civil Engineering
The College of New Jersey
2000 Pennington Road
Ewing, NJ 08628-0718
Tel: (609) 771-2475
Email: bechtela@tcnj.edu

Performing Organization:
The College of New Jersey

Sponsor(s):
University Transportation Research Center (UTRC)

To request a hard copy of our final reports, please send us an email at utrc@utrc2.org

Mailing Address:

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

Board of Directors

The UTRC Board of Directors consists of one or two members from each Consortium school (each school receives two votes regardless of the number of representatives on the board). The Center Director is an ex-officio member of the Board and The Center management team serves as staff to the Board.

City University of New York
Dr. Hongmian Gong - Geography/Hunter College
Dr. Neville A. Parker - Civil Engineering/CCNY

Clarkson University
Dr. Kerop D. Janoyan - Civil Engineering

Columbia University
Dr. Raimondo Betti - Civil Engineering
Dr. Elliott Sclar - Urban and Regional Planning

Cornell University
Dr. Huaizhu (Oliver) Gao - Civil Engineering

Hofstra University
Dr. Jean-Paul Rodrigue - Global Studies and Geography

Manhattan College
Dr. Anirban De - Civil & Environmental Engineering
Dr. Matthew Volovski - Civil & Environmental Engineering

New Jersey Institute of Technology
Dr. Steven I-Jy Chien - Civil Engineering
Dr. Joyoung Lee - Civil & Environmental Engineering

New York University
Dr. Mitchell L. Moss - Urban Policy and Planning
Dr. Rae Zimmerman - Planning and Public Administration

Polytechnic Institute of NYU
Dr. Kaan Ozbay - Civil Engineering
Dr. John C. Falcocchio - Civil Engineering
Dr. Elena Prassas - Civil Engineering

Rensselaer Polytechnic Institute
Dr. José Holguín-Veras - Civil Engineering
Dr. William "Al" Wallace - Systems Engineering

Rochester Institute of Technology
Dr. James Winebrake - Science, Technology and Society/Public Policy
Dr. J. Scott Hawker - Software Engineering

Rowan University
Dr. Yusuf Mehta - Civil Engineering
Dr. Beena Sukumaran - Civil Engineering

State University of New York
Michael M. Fancher - Nanoscience
Dr. Catherine T. Lawson - City & Regional Planning
Dr. Adel W. Sadek - Transportation Systems Engineering
Dr. Shmuel Yahalom - Economics

Stevens Institute of Technology
Dr. Sophia Hassiotis - Civil Engineering
Dr. Thomas H. Wakeman III - Civil Engineering

Syracuse University
Dr. Riyad S. Aboutaha - Civil Engineering
Dr. O. Sam Salem - Construction Engineering and Management

The College of New Jersey
Dr. Thomas M. Brennan Jr - Civil Engineering

University of Puerto Rico - Mayagüez
Dr. Ismael Pagán-Trinidad - Civil Engineering
Dr. Didier M. Valdés-Díaz - Civil Engineering

UTRC Consortium Universities

The following universities/colleges are members of the UTRC consortium.

City University of New York (CUNY)
Clarkson University (Clarkson)
Columbia University (Columbia)
Cornell University (Cornell)
Hofstra University (Hofstra)
Manhattan College (MC)
New Jersey Institute of Technology (NJIT)
New York Institute of Technology (NYIT)
New York University (NYU)
Rensselaer Polytechnic Institute (RPI)
Rochester Institute of Technology (RIT)
Rowan University (Rowan)
State University of New York (SUNY)
Stevens Institute of Technology (Stevens)
Syracuse University (SU)
The College of New Jersey (TCNJ)
University of Puerto Rico - Mayagüez (UPRM)

UTRC Key Staff

Dr. Camille Kamga: *Director, Assistant Professor of Civil Engineering*

Dr. Robert E. Paaswell: *Director Emeritus of UTRC and Distin*guished Professor of Civil Engineering, The City College of New York

Herbert Levinson: *UTRC Icon Mentor, Transportation Consultant and Professor Emeritus of Transportation*

Dr. Ellen Thorson: *Senior Research Fellow, University Transportation Research Center*

Penny Eickemeyer: *Associate Director for Research, UTRC*

Dr. Alison Conway: *Associate Director for Education*

Nadia Aslam: *Assistant Director for Technology Transfer*

Nathalie Martinez: *Research Associate/Budget Analyst*

Tierra Fisher*: Office Assistant*

Bahman Moghimi*: Research Assistant;*
Ph.D. Student, Transportation Program

Wei Hao*: Research Fellow*

Andriy Blagay: *Graphic Intern*

TECHNICAL REPORT STANDARD TITLE PAGE

<table>
<tr><td>1. Report No.</td><td>2.Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
EFFECT OF IMPLEMENTING LEAN-ON BRACING IN SKEWED STEEL I-GIRDER BRIDGES</td><td colspan="2">5. Report Date
9/30/2016</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Andrew Bechtel</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
The College Of New Jersey
2000 Pennington Road
Ewing, NJ 08628-0718</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
49198-21-27</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
UTRC
The City College of New York
137th Street and Convent Avenue
New York, NY 10031</td><td colspan="2">13. Type of Report and Period Covered</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
Skew of the supports in steel I-girder bridges cause undesirable torsional effects, increase cross-frame forces, and generally increase the difficulty of designing and constructing a bridge. The girders experience differential deflections due to the skewed supports, and undesirable effects arise when the girders are linked transversely. Before the placement of the deck, the main method of linking the girders transversely is through the use of cross-frames. The cross-frames are designed to provide stability during construction and distribute transverse loads through the bridge girders; this is their primary role. Cross-frames also help control differential displacement during deck placement and distribute vertical loads in the bridge's elastic and inelastic ranges. The cross-frames are not specifically designed for these tasks; these are the secondary roles of the cross-frames. Lean-On bracing has been proposed to reduce skew effects caused by traditional cross-frames. While having been shown to improve skew effects, the alternative cross-frame designs have not been evaluated on the effect they have on the cross-frames' secondary roles.

This paper describes a study of the effects Lean-On bracing has on the secondary roles of cross-frames. Three-dimensional Finite Element Models were used to perform a study involving changes in skew angle and cross-frame design. The rotation of the girders, maximum cross-frame stresses, load distribution, and differential displacement between the girders were used to characterize the behavior of the bridges. For the bridge type studied, the only major difference in performance was that the maximum cross-frame stresses were reduced for the bridges modeled with Lean-On bracing.</td></tr>
<tr><td colspan="2">17. Key Words
Steel I-Girder, Bracing</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif (of this report)

Unclassified</td><td>20. Security Classif. (of this page)

Unclassified</td><td>21. No of Pages
19</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-69)

DISCLAIMER

AKNOLEDGEMENTS

The author would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Foundation - Ministry of Education of Brazil and The College of New Jersey's Mentored Undergraduate Summer Experience for providing funding for our undergraduate researchers. Specifically, the author would like to thank Alyssa DeSimone, Goedele Van Landegem, and Alexandre Deichmann.

FIGURES

TABLES

ABSTRACT
Skew of the supports in steel I-girder bridges cause undesirable torsional effects, increase cross-frame forces, and generally increase the difficulty of designing and constructing a bridge. The girders experience differential deflections due to the skewed supports, and undesirable effects arise when the girders are linked transversely. Before the placement of the deck, the main method of linking the girders transversely is through the use of cross-frames. The cross-frames are designed to provide stability during construction and distribute transverse loads through the bridge girders; this is their primary role. Cross-frames also help control differential displacement during deck placement and distribute vertical loads in the bridge's elastic and inelastic ranges. The cross-frames are not specifically designed for these tasks; these are the secondary roles of the cross-frames. Lean-On bracing has been proposed to reduce skew effects caused by traditional cross-frames. While having been shown to improve skew effects, the alternative cross-frame designs have not been evaluated on the effect they have on the cross-frames' secondary roles.

This paper describes a study of the effects Lean-On bracing has on the secondary roles of cross-frames. Three-dimensional Finite Element Models were used to perform a study involving changes in skew angle and cross-frame design. The rotation of the girders, maximum cross-frame stresses, load distribution, and differential displacement between the girders were used to characterize the behavior of the bridges. For the bridge type studied, the only major difference in performance was that the maximum cross-frame stresses were reduced for the bridges modeled with Lean-On bracing.

INTRODUCTION
Skew of the supports in steel I-girder bridges can cause undesirable torsional effects. These effects include an overall rotation of the girders, lateral bending stress in the girder flanges, and elevated forces in cross-frames (1). This results in the web of the girder being out of plumb in all but one designed load condition and fatigue problems at the locations of cross-frames, which reduce the useful life of the bridge (2) (3). The torsional effects are caused by differential displacements along the length of each girder. Individually, loading would not cause torsion in the girders, but connecting the girders transversely, either with cross-frames or a concrete deck, links the girders and induces torsion (1). During construction, before the concrete deck has cured, linking the girders transversely is required to provide stability. In the final in-service state, linking the girders transversely provides for redundancy, load distribution, and a load path for transverse loads.

Cross-frames provide the main mechanism used to link girders transversely up until the point where a concrete deck has been placed and cured. Figure 1 gives three typical cross-frame details. The primary (designed) duties of the cross-frames are to provide stability during construction and a load path for transverse forces (4). In order to accomplish these goals, the cross-frames must have stiffness in the transverse direction. Secondarily (non-designed), cross-frames control the profile of the concrete deck when it is being placed, contribute to the distribution of live loads between girders, provide redundant load paths, and contribute to a bridge's inelastic response (4). This requires stiffness in the vertical direction.

The vertical stiffness of the typical cross braces shown in Figure 1 is the main cause of the undesirable skew effects. Reducing the vertical stiffness has been shown to alleviate the undesirable effects of skew. Simply removing the top cords from x-braces has been shown to reduce skew effects (2). The use of Lean-On bracing has been implemented in the field to reduce the effects of skew and the removal of the diagonal chords from the cross-frames has been implemented to prevent undesirable load paths in experimental testing (5) (6). Figure 2 shows an example of Lean-On bracing. Lean-On bracing reduces the number of cross-frames with vertical stiffness. The use of Lean-On bracing has been shown to provide the required stability bracing and to reduce the effects of skew (7, 8). While these methods have been implemented to reduce skew effects, they may prevent the cross-frames from contributing in their secondary roles. In order to fully understand the benefits of cross-frame designs that reduce skew effects, their effects on the secondary roles of cross-frames must be considered.

This paper describes an analytical study of regular and skewed steel I-girder bridges under applied loads using K-Frames and Lean-On bracing to investigate the effects the different cross-frame designs have on load distribution and ultimate capacity. The analytical models used are based on the results of a physical test of ultimate capacity on a 1/5th scale model. The analysis compares different bridge skew angles (0°, 30°, 45°, 60°) and their effects on the behavior of bridges with both cross-frame configurations. The bridges were modeled using Strand7 finite element analysis software. On average, each model contained 248,320 nodes, 11,652 beams and 242,046 plates.

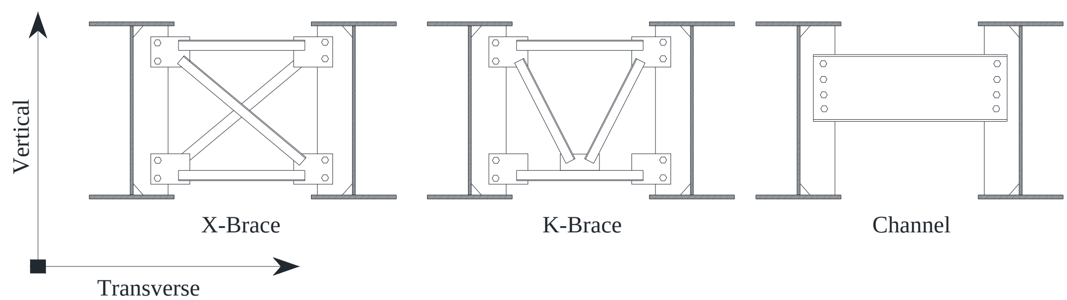


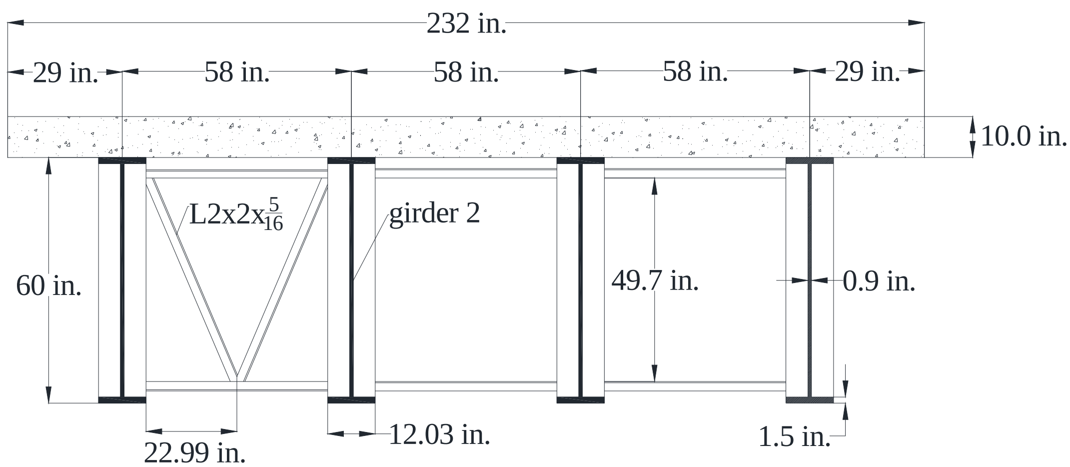
FIGURE 1 Common cross-frame and diaphragm designs

MODELING

The bridge models used in this study were based on the 1/5th scale physical model described in Bechtel et al. (6) (9). This scale physical model bridge was loaded to its ultimate capacity. The bridge failed when the concrete deck fractured; the scale physical model is pictured in Figure 3a. This provided a known failure mode for the bridge models used in this study and verification for the modeling techniques. The general cross-section of the bridge was scaled up and held constant for each bridge. Figure 2 shows the general bridge geometry of the computer model. While the skew of the bridge was increased, the girder spacing, girder length, and deck thickness were held constant. Changes in these parameters could cause a change in the failure mode.

Material Properties

Figure 4 shows the simplified material properties used in the models. The material properties were based on those measured in Bechtel et al (6) (9). The steel has an elastic modulus of 29,000 ksi, yields at a stress of 56 ksi, has a perfectly plastic yield plateau, and linearly strain hardens to a stress of 65 ksi. When a nonlinear steel model was implemented, von Mises yield criterion was used. Steel was used for the girders, cross-frames, end diaphragms, and the concrete formwork. The concrete was modeled as linear elastic with a modulus of 5,260 ksi. The ultimate compressive stress was 5.4 ksi, and the ultimate tension stress was 0.26 ksi. The ultimate tension stress was taken as $3.65\sqrt{f'_c\,(\text{psi})}$ (10). The concrete was modeled as a nonlinear elastic material with a maximum stress (11). This model uses the principal strains to determine the behavior of the concrete material, allowing it to behave differently in tension and compression (11). After the concrete reached its ultimate stress, in either tension or compression, the material was given a plastic behavior. In reality, concrete stress would reduce to zero. The plastic behavior served to create a more stable model that could be evaluated statically. While the concrete in Bechtel et al. was reinforced, the reinforcement was not included in these models (6). The purpose of the study was comparison, and all models were created in the same manner. The concrete material model and the omission of reinforcement created a model that solved more rapidly and displayed the deflection characteristics and failure mode observed in Bechtel et al (6). Figure 3a shows the failure of the model bridge compared to finite element results. The white area shows where the deck has exceeded the tension cracking stress in the transverse direction. The transverse tension in the deck is due to the applied load being distributed to the other girders in the bridge.



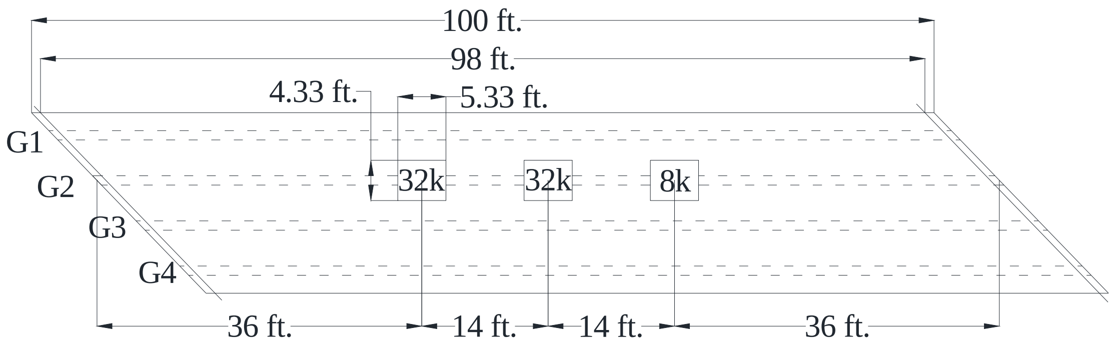
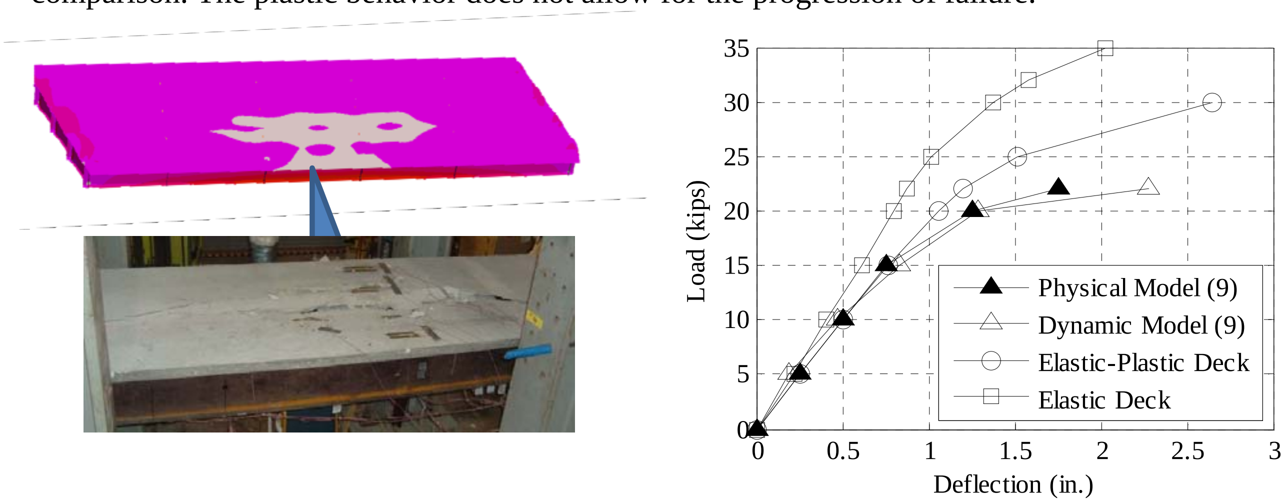


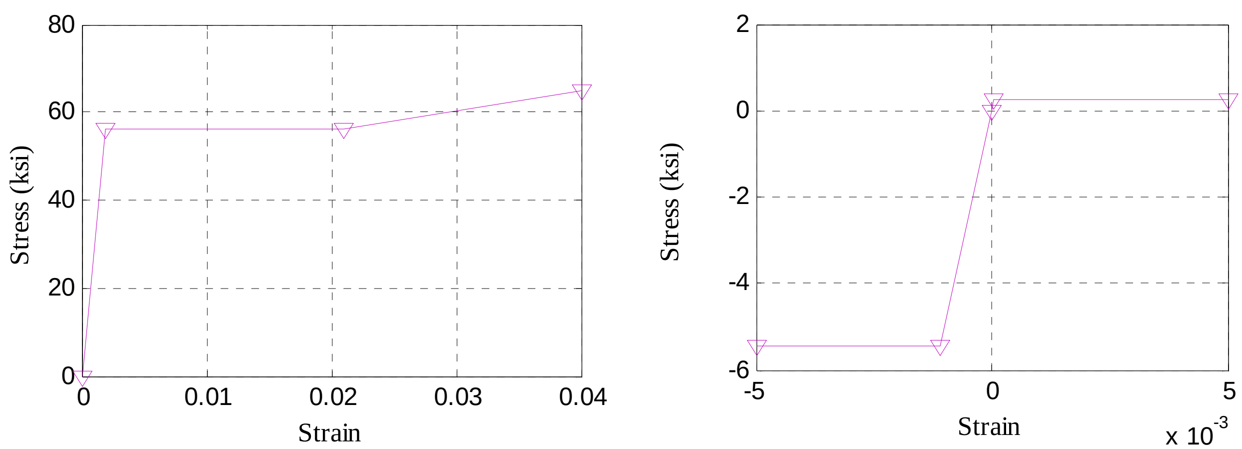
FIGURE 2 General bridge geometry

Figure 3b compares the load deflection behavior of Girder 2 from the physical test to three different analytical models with different deck properties. The best agreement can be achieved with an explicit dynamic model (9). This type of model is incredibly time and resource intensive. Since the goal of the study was comparison, it was desired to develop a simplified static model which could identify the failure mode. Giving the deck('s) linear elastic material properties made the model overly stiff. The deflection behavior of the model with linear elastic deck properties begins to deviate from the physical test at a load of 5 trucks. Given the concrete deck elastic perfectly plastic behavior resulted in better agreement with the physical test. The load deflection behavior does not deviate until loads greater than 15 trucks. Making the concrete material properties elastic and then plastic allows the models to capture the initiation of the deck failure while maintaining model stability, and this was deemed adequate for the purpose of comparison. The plastic behavior does not allow for the progression of failure.



a) Deck Failure b) Load deflection behavior of G2

FIGURE 3 Failure crack Bechtel et al. and analytical model comparison (9)



a) Steel Properties b) Concrete Properties

FIGURE 4 Material Properties

Model Layout and Cross-Frame Design

Simply supported bridge models were created at 0°, 30°, 45°, and 60° skews. The girder and deck cross-sections were held constant. The girders had a height of 60 in. and a web thickness of 0.9 in. The total flange width was 12.03 in. and the thickness of the flange was 1.5 in. The girders were 100 ft. (1200 in.) long with a span of 198 ft. (1176 in.). The stiffeners were full depth and 1 in. thick. The concrete deck was 10 in. thick. The rigid supported diaphragms had the same cross-sections as the girders and ran from support to support with the skew. The girders and cross-frames were designed with no load fit.

The maximum cross-frame spacing was assumed to be 25 ft.; for the given girders this spacing met the local buckling requirements in the AASHTO LRFD Bridge Design Specifications (12). K-Frames were used because the ratio of girder spacing to girder depth was greater than 1.5. The cross-frames were designed using the American Institute of Steel Construction Specification for Single Angle Members (13). This was the method used to design the cross-frames for the physical model. The members were sized using the lateral wind loads (12), and an L2x2x5/16 angle was used for all portions of the intermediate cross-frames. This was the method used to size the cross-frames in the physical model. The concrete form was composed of 1/8-in. thick steel and supported with L2 ½ x 2 ½ x ½ steel angles at every foot along the length.

Figure 5 represents the girders at different skewed angles and their cross-frame configurations. The Lean-On braces were laid out in the same manner as in Helwig, and Liqun (7). All cross-frames were laid out perpendicular to the girders. This mimics the cross-frames in the physical model. The orientation of the cross-frames to the girders was not evaluated as a variable. The bridge with no skew consisted of nine intermediate K-Frames at three positions; these were reduced to three intermediate K-Frames for the Lean-On design. The bridge with a 30° skew required twelve K-Frames in the conventional layout and four K-Frames in the Lean-On layout. The bridges with 45° skew required eleven K-Frames for the K-Frame design and four K-Frames in the Lean-On design. This bridge required less K-Frames due to the skew and maximum allowable distance between cross-frames. For the 60° skewed bridge, due to the larger skew and maximum allowed length between cross-frames, the layout of the cross-frames was reduced to ten K-Frames for the conventional design and four K-Frames for the Lean-On design.

Model Staging

To better represent a real structure, construction phasing was accounted for in the models. This was achieved by creating groups within each model and activating and deactivating these groups when appropriate. The results of each stage were used as the initial conditions of each subsequent stage. Table 1 details the loads and components present in each stage of the bridge, and Figure 6 gives a visual for selected stages during this process. Stage 1 accounted for the gravity load in the girders and the cross-frames. The formwork was installed in Stage 2. The concrete deck was poured in Stages 3 through 7. Figure 7 shows the order the pressures representing the wet concrete were applied to the model. The concrete pressures were applied moving transversely across the bridge to increase differential displacement in the girders and stress in the cross-frames. In Stage 8, the formwork and applied pressures were removed from the model and replaced with the solid concrete deck. This was the first point where the concrete was given stiffness. In Stage 9, three pressure loads equal to the three axels of the AASHTO HS-20 truck were applied mid-span on Girder 2. The pressure areas were scaled from Bechtel et al.

(9). In Stages 10 until failure, the pressure load was increased by one truck. Stages 1 through 9 were evaluated allowing for nonlinear geometry, and subsequently Stages 9 to failure were evaluated using nonlinear material properties. Nonlinear geometry was considered for the construction phase to evaluate stability issues with the formwork and construction. The stresses were checked to ensure they remained well below the yield stress. Nonlinear material properties had to be considered in order to evaluate the ultimate capacity, but geometric nonlinear behavior was neglected. The nonlinear geometry would have allowed the cross-frames to buckle, but this may have made comparison between the two different cross-frame details more difficult. Especially if one cross-frame were to buckle and the other did not. Buckling of a cross-frame member could easily be corrected for in the design of the cross-frames. It would not help to demonstrate a difference between the two different cross-frame types.

Failure was determined when the strain in the concrete deck exceeded the strain at which the maximum tension stress occurred. In Figure 3a, the failure area of the model, represented in white, can be compared to the failure in the physical model.

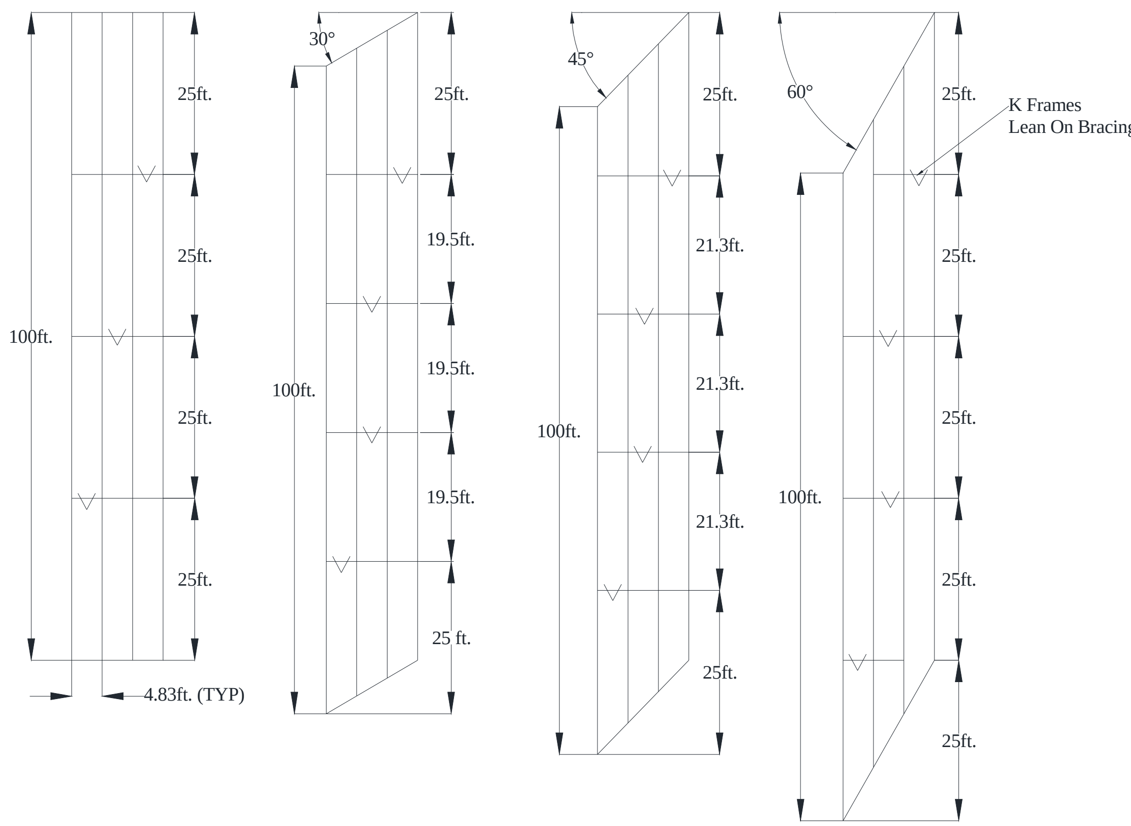


FIGURE 5 Layout of cross-frames

TABLE 1 Model Staging

	Stage									
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	To failure
	Structural Steel	Form Work	Concrete Deck Placement					Deck Cured	Truck Loading: 72 kips/ truck	
Gravity	On →	→	→	→	→	→	→	→	→	→
Concrete Pressure			Load Case 1	Load Case 2	Load Case 3	Load Case 4	Load Case 5			
Truck Load									1	Increases 1 / Stage
Non-Linear Analysis	NLG[1] →	→	→	→	→	→	→	→	→	NLM[2]
Girder	Active →	→	→	→	→	→	→	→	→	→
Cross-Frame	Active →	→	→	→	→	→	→	→	→	→
End Diaphragm	Active →	→	→	→	→	→	→	→	→	→
Formwork	Inactive	Active →	→	→	→	→	→	Inactive →	→	→
Concrete Deck	Inactive →	→	→	→	→	→	→	Active →	→	→
[1]NLG= Non-linear Geometry, [2]NLM= Non-linear Material										

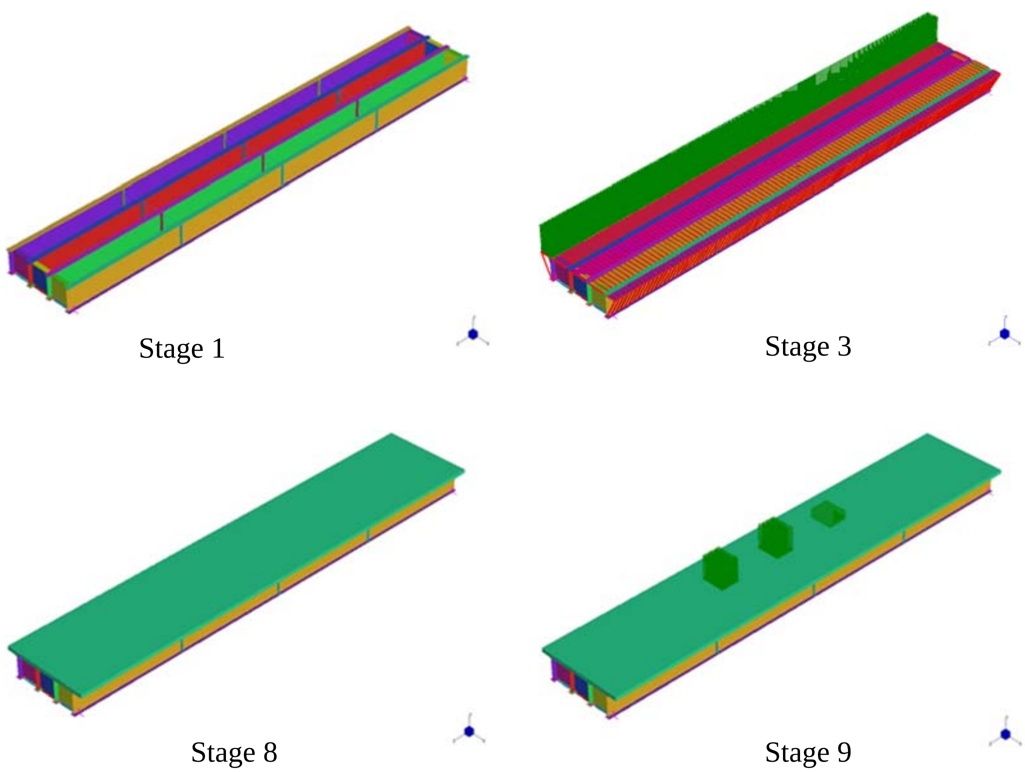


FIGURE 6 Model Staging

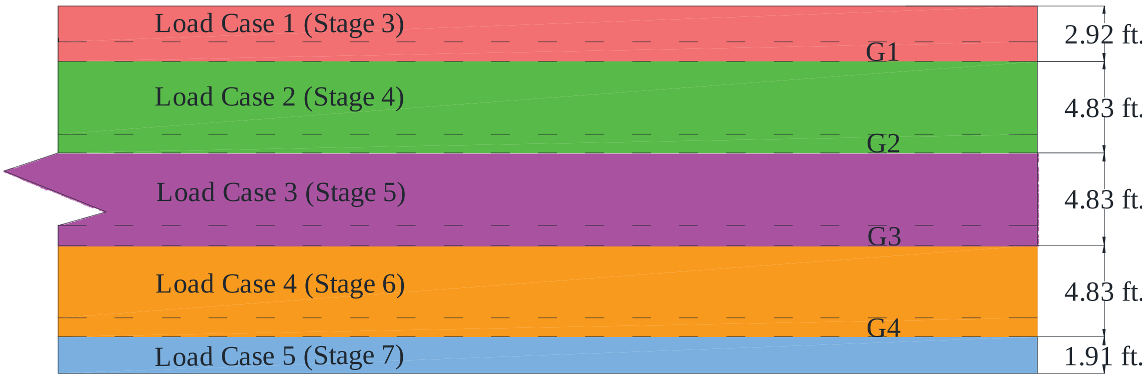


FIGURE 7 Concrete placement loading

RESULTS AND ANALYSIS

The purpose of this study was to evaluate the effectiveness of Lean-On bracing in respect to the secondary roles of cross-frames and the reduction of skew effects. Differential displacement and load distribution were evaluated to determine the effect Lean-On bracing has on the secondary roles of cross-frames. When the skew in the bridge increased, the stresses in the cross-frames and the rotation of the girders increased. The stresses in the cross-frames and maximum girder rotation were analyzed to determine the effectiveness of Lean-On bracing in reducing the effects of skew.

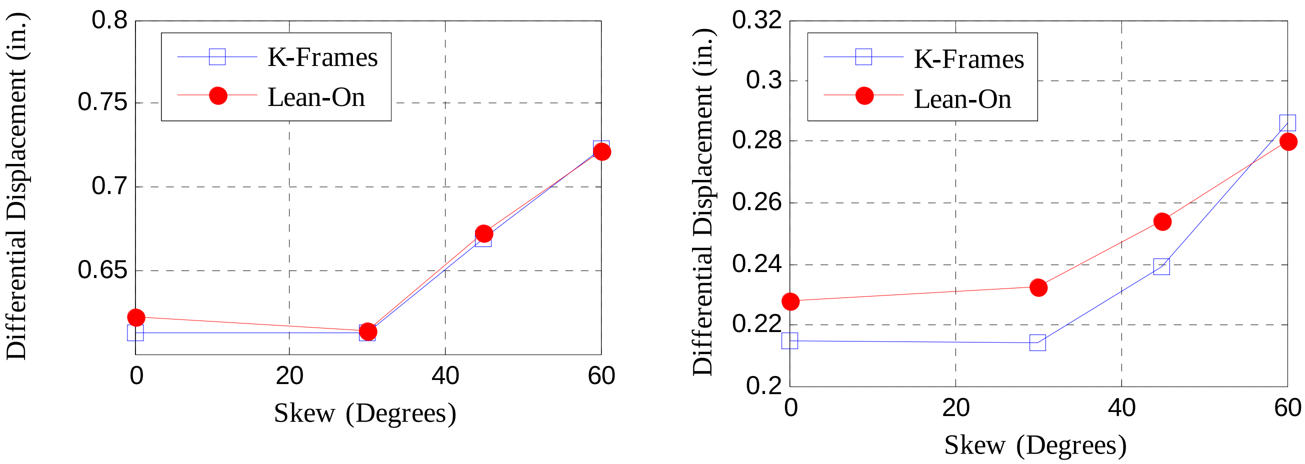
Ultimate Capacity

The ultimate capacity of each model was governed by failure of the deck. Failure was evaluated by observing strain in the transverse direction. The first crack was determined when the strain in the concrete deck exceeded the tension strain, 0.000053. This strain corresponds to the ultimate tension stress. Failure was determined when the area of the deck with the strain exceeding 0.000053 grew to match that observed in the scale model tested in Bechtel et al. (6). For all skewed bridges, except the bridge with K-Frames and no skew, the first cracks formed when 4 trucks were applied, and failure occurred under a load of 6 trucks. First cracking occurred for the bridge with K-Frames and no skew at a load of 5 trucks, and ultimate failure occurred under 7 trucks. Generally, the use of Lean-On bracing did not affect the cracking or ultimate capacity.

Differential Displacement

Figure 8a shows the maximum differential displacement between all girders for each skew and cross-frame configuration. The differential displacement was found by summing the change in displacement in the transverse direction at two-inch increments along the length of the bridge. The maximum displacement occurred between girders 1 and 4. The maximum differential displacement occurred during Stage 4 for the bridge without skew and during Stage 5 for the skewed bridges. Figure 8a shows that bridges at a higher skew experienced a higher absolute differential displacement. It was observed that there was no significant difference between the K-Frame and Lean-On designs for the absolute differential displacement.

Figure 8b displays the relative differential displacement for each skew and both cross-frame configurations. The maximum relative differential displacement was found by comparing adjacent girders. Maximum relative differential displacement occurred between girders 1 and 2 for all bridges. The relative differential displacements were analyzed during the construction phase and it was determined that they took place during Stage 4 for the bridges at 0° and 30° skew and they took place during Stage 5 for the 45° and 60° skewed bridges. The graph shows that the relative differential displacement increased as the skew in the bridge increased. The Lean-On bracing resulted in an increase of approximately 0.01 inches in relative differential displacement. The differences between the K-Frames and the Lean-On bracing designs for relative differential displacement were small enough to be considered insignificant.



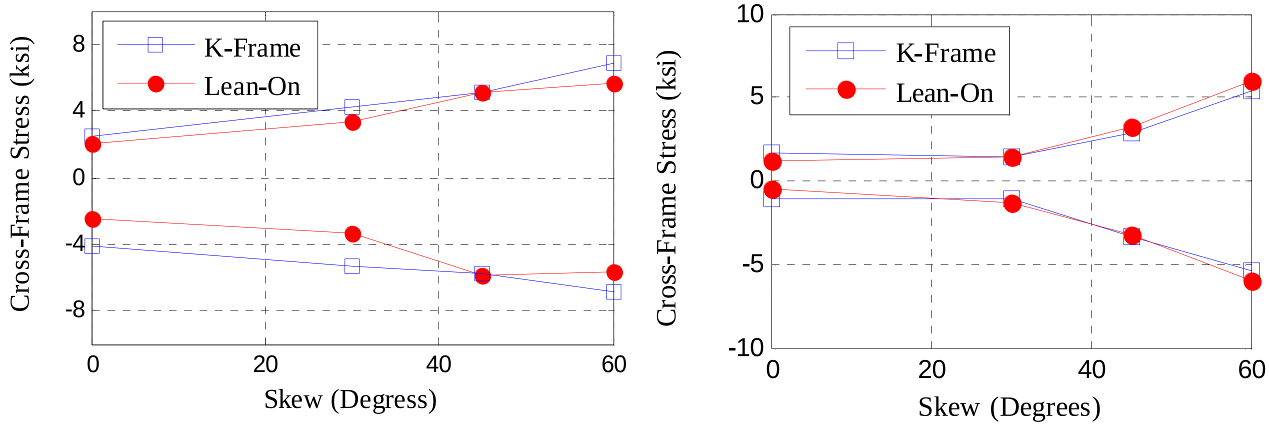
a) Max. Absolute Differential Displacement b) Max. Relative Differential Displacement

FIGURE 8 Differential Displacement

Cross-Frame Stress

Figure 9 shows the maximum axial cross-frame stresses in both tension(+) and compression(-). Figure 9a shows the maximum cross-frame stresses during the placement of the deck. The maximum value for each bridge occurred between Stages 3 and 5. During the placement of the deck, the axial cross-frame stresses were higher in the K-Frames. The K-Frame layout resulted in a stress increase of approximately 2 ksi for the compression members and approximately 1 ksi for the tension members, except for at 45° skew. The highest cross-frame stresses occurred for the 60° skewed bridge at -6.3 ksi in compression and 6.8 ksi in tension. As the skew in the bridge increased, the cross-frame stresses increased as well.

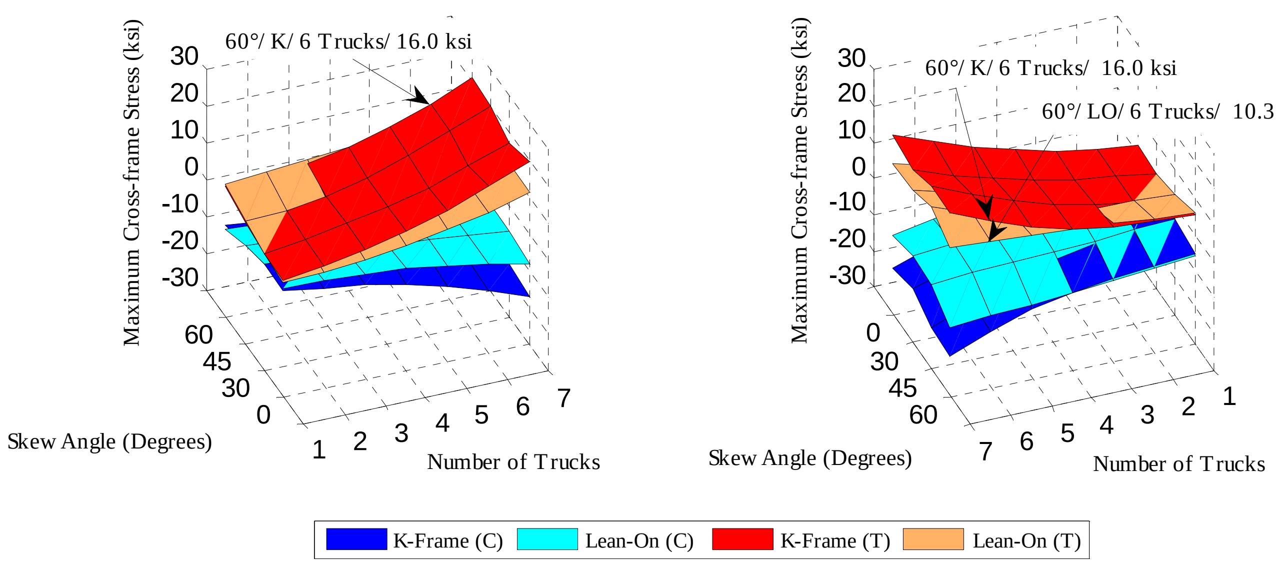
Figure 9b shows the axial cross-frame stresses when one truck load was applied. While the stresses continued to increase with skew, there was not a difference in stress between the K-Frame and Lean-On configurations. The load of one truck is comparatively less than the weight of the uncured concrete deck.



a) Construction Phase: Stages 3-5 b) 1 Truck: Stage 9

FIGURE 9 Max cross-frame stress

Figure 10 shows the maximum axial stress in the cross-frames for each skew angle and cross-frame configuration from 1 truck (Stage 9) to failure. The tension stresses are represented by the letter "T" and the compression stresses by the letter "C". While most bridges failed at 6 trucks, Figure 10 shows cross-frame stresses up to 7 trucks for comparison. The stresses in the cross-frames increased as more trucks were added to the deck of the bridge and as the skew was increased. The implementation of Lean-On bracing resulted in lower cross-frame stresses. The bridges with 60° skew and K-Frames saw the highest stresses (16.0 ksi. tension and -14.5 ksi. compression at 6 trucks). The implementation of Lean-On bracing reduced these stresses by 36% and 29% in tension and compression respectively.



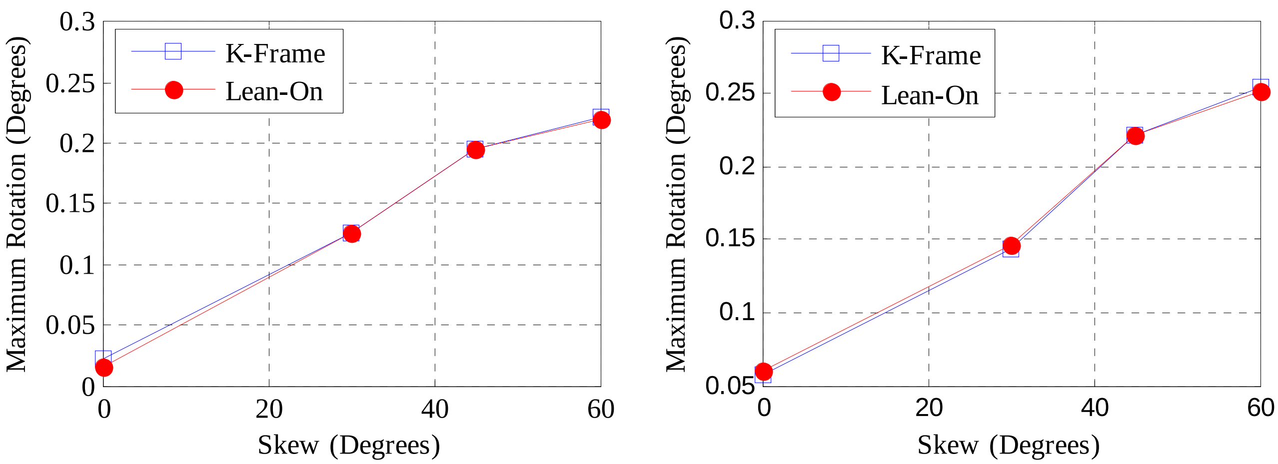
a) View 1 b) View 2

FIGURE 10 Max cross-frame stresses 1 truck (Stage 9) to ultimate

Rotation

Figure 11a shows the maximum rotation that occurred at Stage 7, the end of the construction phase, for all analyzed bridges. The maximum rotation was determined by finding the maximum displacement in the transverse direction in the flanges and comparing this to the original coordinates of the girder. Maximum transverse displacement occurred in the bottom flange. The change in the angle between the top of the web and the edge of the flange was calculated as girder rotation. The maximum rotation increased as skew of the supports increased. Maximum rotation was not significantly affected by the implementation of Lean-On bracing.

Figure 11b shows the maximum rotation at each skew when one truck was applied. The graph shows that after one truck was loaded, the bridge at a higher skew resulted in a higher rotation. This was not affected by the cross-frame design. The Lean-On bracing did not have a significant effect on the rotation of the girders.



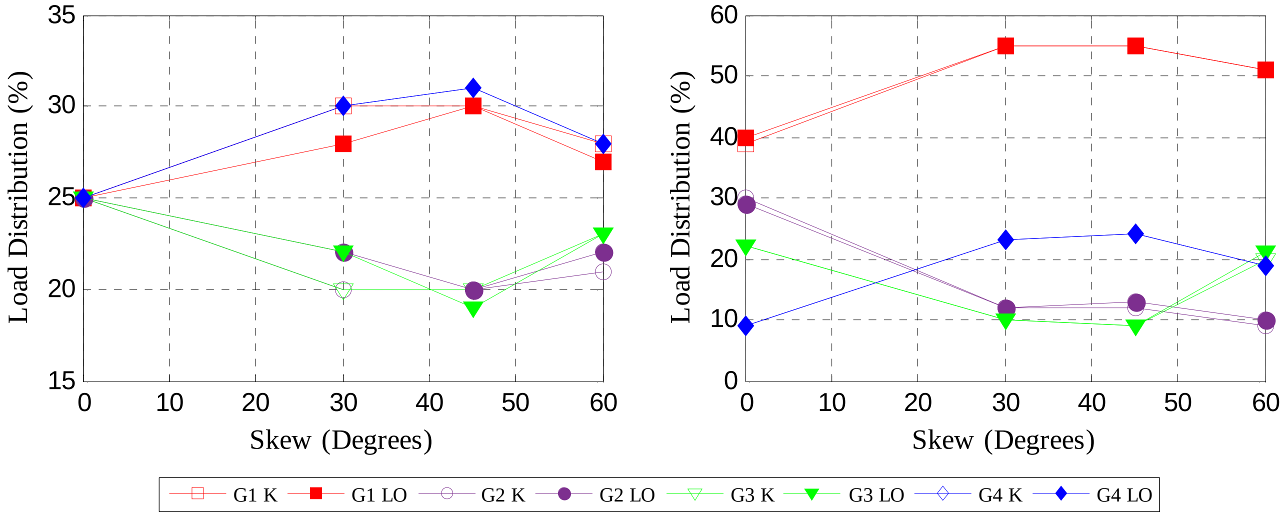
a) Deck placement completed: Stage 7 b) 1 truck load: Stage 9

FIGURE 11 Max girder rotation

Load Distribution

Figure 12a shows the load distribution in Stage 8, where the bridge is fully constructed with the cured concrete deck. All loads were evenly distributed for the bridge without skew. When the supports were skewed, the edge girders carried more load than the inside girders. Lean-On bracing showed a load distribution that was slightly more evenly distributed between the girders, as compared to the K-Frame layout, which varied more.

Figure 12b shows the load distribution for the bridges after one truck load was applied, Stage 9. The plot shows that for all bridge types, Girder 1 carried the largest percentage of the load. This was due to the off center loading. It was observed that the bridge without skew behaved differently than the skewed bridges. For the bridge at 0° skew, Girder 2 carried the second largest load, followed by Girder 3, and then Girder 4. For the skewed bridges at 30° and 45°, Girder 4 carried more load than Girders 2 and 3. This is because the support at Girder 4 in these bridges was located closer to the applied load. For the 60° skewed bridge, the load was closer to Girder 3, therefore this girder carried more load. As the plot shows, the type of cross-frame configuration did not greatly affect the load distribution of the bridges.



a) Deck cured: Stage 8

b) 1 truck: Stage 9

FIGURE 12 Load distribution

Figure 13 shows the change in the truck load distribution for girders transversely connected with K-Frames and Lean-On bracing, respectively. Data is shown for 1 to 7 applied truck loads. The load distributions in the edge girders (1 and 4) and in the center girders (2 and 3) showed similar trends as the skew angle increased. For the skewed bridges, the portion of truck load that Girders 1, 2 and 4 carried decreased while Girder 3's truck load increased. As the load increased and the deck started to crack, its ability to distribute the load to the girders decreased and Girder 2 began to carry a larger percentage of the load. The loads carried by Girders 1 and 4 decreased and the loads carried by Girders 2 and 3 increased. Girder 3 for the bridge with 60° skew did not follow this trend; it carried more load than Girder 2. For this bridge, the truck load is closer to Girder 3's support as compared to the other bridges. The Lean-On bracing did not show a pronounced difference in the distribution of the loads.

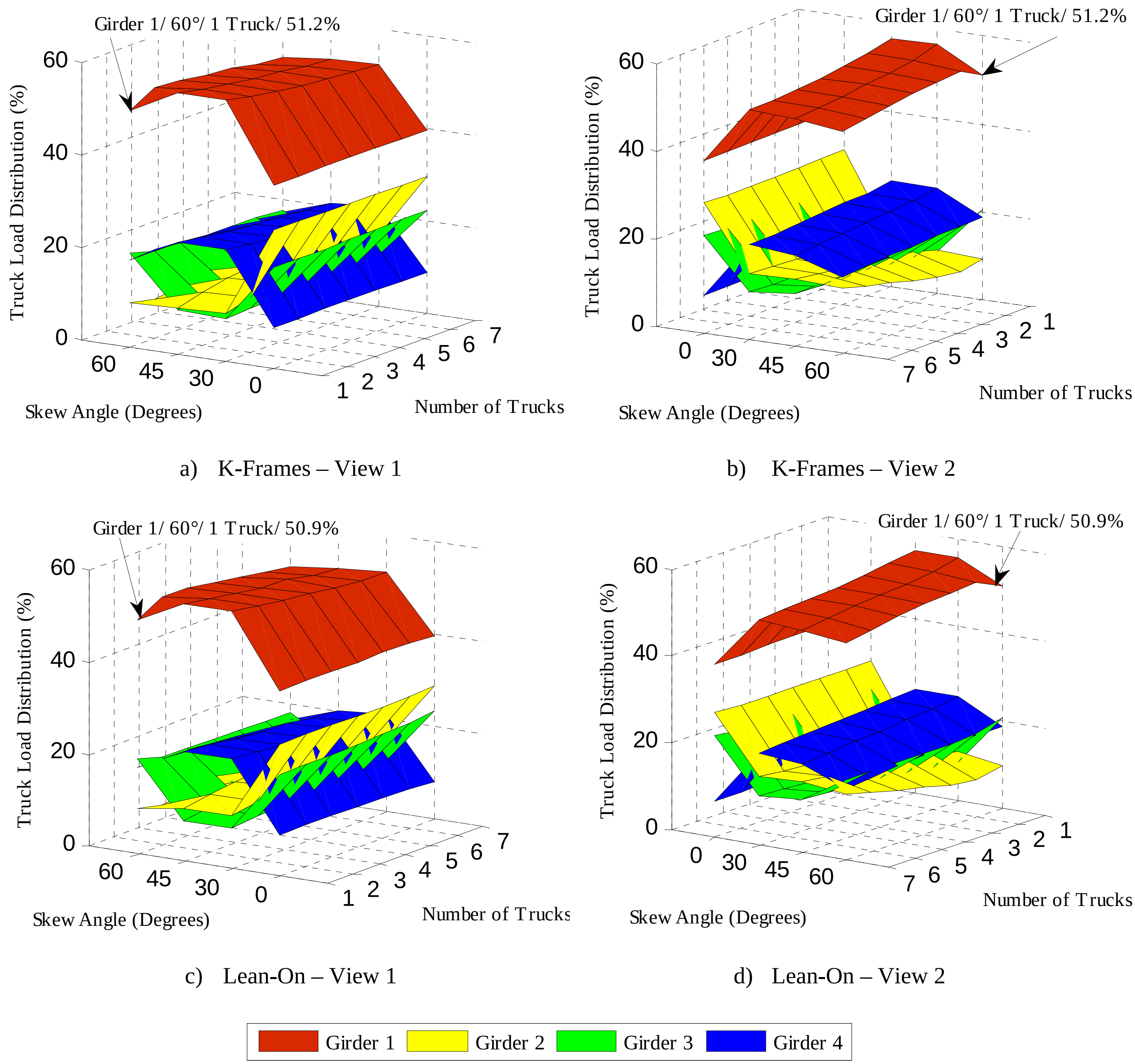


FIGURE 13 Truck load distribution

CONCLUSIONS

This research showed that Lean-On bracing for the bridge type studied did not have a significant effect on the secondary roles of the cross-frames. No significant change was observed in the differential displacement between girders or the distribution of the vertical loads. The alternative cross-frame configuration did not affect the ultimate capacity of the bridges. Failure occurred under the same applied load for each bridge design.

There was a difference in the cross-frames' stresses when comparing Lean-On bracing and K-Frame bracing. The axial stresses in the Lean-On bracing were generally lower than in the K-Frame configuration. In the construction phase, the Lean-On bracing decreased cross-frame stresses by approximately 25 %. For the application of 1 truck the reduction was only 3%. There was no significant difference in the maximum rotation of the girders when Lean-On bracing was implemented. Generally, there was no adverse effects from implementing Lean-On bracing, and Lean-On bracing systems have the advantage of using less material and having fewer connections. This makes them easier to fabricate and assemble. It also reduces dead load.

This study focused on the effects of Lean-On bracing in skewed steel I-girder bridges. The conclusions in this paper are only relevant when applied to this type of bridge structure. Future work could be done to assess the effects of Lean-On bracing in bridges with different dimensions and failure modes.

References

1. Colletti, D. Chavel, B., Gatti, W. The Challenges of Skew In *Transportation Research Board 2011 Annual Meeting Compendium of Papers*

2. Ozgur, C. *Influence of Cross-Frame Detailing on Curved and Skewed Steel I-Girder Bridges*. PhD Dissertation, Georgia Institute of Technology, 2011

3. Roddis, W. M. K., Winters, E. *Cross-Frame Diaphragm Bracing of Steel Bridge Girders* Kansas Department of Transportation Report No. K-TRAN: KU-01-2, 2008

4. McConnell, J. Radovic, M., Ambrose, K. *Cross-Frame Forces in Skewed Steel I-Girder Bridges: Field Measurements and Finite Element Analysis.* Delaware Center for Transportation DCT-241, 2014

5. Fasl, J., Romage, M., Helwig, T., Herman, . R., Frank, K. Field Measurements on Steel Girder Bridge with Skewed Supports Utilizing Lean-On Bracing *Structures Congress 2009: Don't Mess with Structural Engineers*, ASCE pgs. 125-134

6. Bechtel, A.; McConnell, J.; and Chajes, M. Destructive Testing and Finite Element Analysis to Determine the Ultimate Capacity of Skewed Steel I-Girder Bridges, *Transportation Research Record*, Vol. 2131, 49-56. 2009

7. Helwig, Todd A., and Liqun Wang. Cross-Frame and Diaphragm Behavior for Steel Bridges with Skewed Supports. No. Research Report 1772-1. 2003.

8. Quadrato, Craig, Weihua Wang, Anthony Battistini, Andrew Wahr, Todd Helwig, Karl Frank, and Michael Engelhardt. Cross-frame connection details for skewed steel bridges. No. FHWA/TX-11/0-5701-1. 2010.

9. Bechtel, A. McConnell, J., Chajes, M. (2011). Ultimate Capacity Destructive Testing and Finite-Element Analysis of Steel I-Girder Bridges *ASCE Journal of Bridge Engineering* Vol 16(2). 2011 Pgs. 197-206

10. Chitnuyanondh L., Rizkalla, S., Murray, D.W. MacGregor, J. G. *An Effective Uniaxial Tensile Stress-Strain Relationship for Prestressed Concrete*. Structural Engineering Report No. 74. University of Alberta. 1979

11. *Strand7 Theoretical Manual*, Strand7 Pty Ltd. Sydney Australia

12. *AASHTO LRFD Design Specifications*, 2012 Washington, D.C.

13. American Institute of Steel Construction, Inc. *Load and Resistance Factor Design (LRFD) Specification for Single-Angle Members* (No. S351L), Chicago, IL. 2000.

University Transportation Research Center - Region 2

Funded by the U.S. Department of Transportation

Region 2 - University Transportation Research Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: (212) 650-8050
Fax: (212) 650-8374
Website: www.utrc2.org