Design and Construction of Modern Curved Bridges

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UTCA Report Number 01223
December 31, 2002
The overall objectives of this project were to investigate and synthesize state-of-the-art practice for the efficient design and construction of curved bridges, and to identify research needs regarding strength and stability of curved bridges. The project resulted in progress towards establishing a curved steel bridge stability research program within The University of Alabama system. The work was conducted by graduate students whose efforts have resulted in several papers and presentations. The project enabled the investigators to participate in national level conferences and meetings. Research literature was collected that will facilitate continued research efforts. The planning, design, fabrication, and construction of a local curved I-girder bridge flyover was studied to gain a better understanding of practical challenges associated with curved bridge design and construction. Curved I-girder and box girder stability topics that can be tackled within a university research environment were identified through the background research and interaction with industry leaders. A meeting with Alabama Department of Transportation bridge engineers provided insight into the research and education needs and interests of Alabama. The project facilitated interaction with prominent curved bridge researchers, industry leaders, and state and federal government division and program managers. This report concisely summarizes the activities and accomplishments of the research team. Technical results of the effort will be disseminated through conference presentations and proceedings, journal publications, student theses and dissertations, and the final report of a follow-on project, UTCA Project 03228, “Stability of Curved Bridges during Construction.”

The generation of so much information on this topic and contacts with so many experts in the field made the Principal Investigator uniquely prepared to advance the state of practice of curved bridge design in Alabama. Future civil engineering students and bridge owners (ALDOT, counties, and cities) will certainly benefit from this knowledge.
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Executive Summary

As the population of Alabama’s major metropolitan areas grows, there will be a need for smooth traffic flow transitions into and out of interstate highways and other major roadways. Optimum traffic flow designs are essential for increased safety as well as increased efficiency of the roadway system. In urban areas, this inevitably requires curved roadway alignment, and very often requires bridges to be constructed on curved alignment. In fact, nationwide, over one-third of all steel superstructure bridges constructed today are curved. But, design and construction of curved bridges is far more complicated and problematic than that of the typical straight bridge.

The overall objectives of this project were to investigate and synthesize state-of-the-art practice for the efficient design and construction of curved bridges, and to identify research needs regarding strength and stability of curved bridges. The project resulted in progress towards establishing a curved steel bridge stability research program within The University of Alabama system. The work was conducted by graduate students whose efforts have resulted in several papers and presentations. The project enabled the investigators to participate in national level conferences and meetings. Research literature was collected that will facilitate continued research efforts. The planning, design, fabrication, and construction of a local curved I-girder bridge flyover was studied to gain a better understanding of practical challenges associated with curved bridge design and construction. Curved I-girder and box girder stability topics that can be tackled within a university research environment were identified through the background research and interaction with industry leaders. A meeting with Alabama Department of Transportation bridge engineers provided insight into the research and education needs and interests of Alabama. The project facilitated interaction with prominent curved bridge researchers, industry leaders, and state and federal government division and program managers. This report concisely summarizes the activities and accomplishments of the research team. Technical results of the effort will be disseminated through conference presentations and proceedings, journal publications, student theses and dissertations, and the final report of a follow-on project, UTCA Project 03228, “Stability of Curved Bridges during Construction.”
1.0 Introduction

1.1 General

As the population of Alabama’s major metropolitan areas grows, there will be a need for smooth traffic flow off of interstate highways and other major roadways. This will inevitably require curved roadway alignment, and will often require curved bridges. In fact, nationwide, over one-third of all steel superstructure bridges constructed today are curved. Efficient design of curved bridges results in a superstructure that uses horizontally curved beams.

In the early days of curved bridge design and construction, bridge superstructures supporting curved roadway alignment were comprised of short straight girders linked together at the supports. This resulted in inefficient use of very short spans between support piers. As the technology for designing and fabricating curved girders became available, it became possible to design curved bridges with much greater distances between supports.

Today, curved girders are widely used in bridge superstructures. The designer has many choices including material (concrete vs. steel), cross-section shape (tub girder vs. I-beam), etc. Furthermore, the past three decades have resulted in advances in optimizing curved bridge design, resulting in innovative, aesthetically pleasing structures. However, due to the simple addition of curvature, the design and construction of bridges becomes immensely more complicated than that of straight bridges. While the girders, stringers, and floor beams of straight bridges can be designed by systematically isolating each member and applying standard loads, curved bridges must be designed with careful consideration to system-wide behavior. In essence, the addition of curvature adds torsion to the system that results in significant warping and distortional stresses within the member cross-sections. Furthermore, “secondary members” such as cross frames and diaphragms that provide stability in straight bridges become primary load carrying members in curved bridges.

Although the design of curved bridges is much more complex than that of straight bridges, there are no requirements specific to the design of curved bridges integrated into the American Association of State Highway Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (AASHTO 1992). There is, however, the “Guide Specifications for Horizontally Curved Highway Bridges,” which was first adopted in 1981 (AASHTO 1993). This “guide” is widely recognized to be outdated, disjointed, and difficult to use. Several significant research projects have been conducted over the past few years including the Federal Highway Administration (FHWA) “Curved Steel Bridge Research Project (CSBRP)” and the National Cooperative Highway Research Program (NCHRP) Project 12-38, “Improved Design Specifications for Horizontally Curved Steel Girder Highway Bridges.” Currently, NCHRP Project 12-52, “LRFD Specifications for Horizontally Curved Steel Girder Highway Bridges,” is being conducted by Modjeski & Masters to prepare specifications for the design and construction of horizontally curved steel girder bridges (for both I- and box girders) in a calibrated load and
resistance factor design (LRFD) format that can be recommended to AASHTO for adoption (www.modjeski.com). Furthermore, many states have recently conducted or supported research on curved bridge design and construction. The only other bridge design document in the world that specifically addresses curved bridge design is the Japanese “Guidelines for the Design of Horizontally Curved Girder Bridges” by the Hanshin Expressway Public Corporation (Hanshin 1988). Several researchers, including the primary author of this report (Davidson), have demonstrated disparity in the strength formulations between the Japanese and American curved bridge design guides, which further emphasizes the need for additional research.

In addition to improving design equations for curved bridges, another area that has been widely recognized for further research is that of lifting and transporting curved girders during construction. By far, the most frequent problems are encountered during construction. The problems are typically more severe and more common than those encountered during the construction of straight bridges. During the construction of straight bridges, girders and stringers are easily erected by one crane using one or two pick-up points, or by two cranes using one pick-up point each. The individual straight girders can simply be set in place with little concern for instability. Lifting and setting presents little difficulty for straight beams where the center of gravity is coincident with the centroidal axis of the beam cross-section. But for horizontally curved girders, the center of gravity is non-coincident with the cross-section centroid. Depending on the lifting/support mechanism used, significant torsional stresses and minor-axis bending stresses may be induced. The handling and erection of horizontally curved girders requires engineering expertise beyond that needed for the construction of straight bridges. Engineers not experienced in the design of curved bridge systems often make the mistake of assuming that behavior and design is the same as that for straight bridges. Instability during construction can easily translate into unsafe conditions for construction workers, not to mention unforeseen additional costs.

Because of the increasing demand for curved bridges combined with challenges of design and construction, there is need to investigate and synthesize state-of-the-art practice for the efficient design and construction of curved bridges. This report summarizes the activities and accomplishments of a first phase project aimed at establishing a curved steel bridge research program within The University of Alabama system. A follow-on project, UTCA Project 03228, “Stability of Curved Bridges during Construction,” is currently underway using the contacts, literature survey, and research needs synthesis of this project. Technical results of the effort will be disseminated through conference presentations and proceedings, journal publications, student theses and dissertations, and the final report of UTCA Project 03228.

1.2 Objectives

The overall objectives of this project were to investigate and synthesize state-of-the-art practice for the efficient design and construction of curved bridges and to identify research needs regarding strength and stability of curved bridges. Additional goals of the project included:
• Develop relationships with Alabama Department of Transportation (ALDOT) bridge engineers, FHWA program managers, prominent curved bridge researchers, and industry leaders;

• Identify research needs and topics suitable for graduate research;

• Identify technology transfer and continuing education needs of ALDOT and the bridge design industry of the region;

• Contribute to bridge stability research needs through graduate student research;

• Identify potential sources of future support;

• Transfer project results to stakeholders.

1.3 Scope and Project Description

1.3.1 Tasks

The four tasks of the project work plan and a synopsis of the accomplishments associated with each are described below. The work was accomplished over a 16-month period beginning September 1, 2001.

**TASK 1. Synthesis of current practice**

The data-gathering effort involved investigating the current state-of-the-art curved bridge design and construction practice around the country. The usual avenues of collecting information such as publication database searches and Web-based searches were used. However, the synthesis largely depended upon direct contacts by the investigators. Many states have conducted investigations to improve the design and construction of curved bridges and the resulting reports of such projects often do not show up in the typical library or journal database search. Investigators at the University of Texas, the University of Houston, the University of Pittsburgh, and the University of Pennsylvania, for example, were contacted, as well as design industry experts. Other materials such as workshop materials developed by the Structural Stability Research Council were collected and reviewed.

**TASK 2. Identification of research needs**

This task involved reviewing recent literature and meeting with research authorities and industry leaders. The objective was to identify needs specific to Alabama as well as areas of national need. A meeting with ALDOT bridge engineers helped to identify how university expertise can help with their needs. The investigators also contacted design firms, manufacturers, and construction companies in the region to establish relationships and to understand their issues regarding curved
bridge design and construction. A local curved I-girder bridge project was studied to gain a better understanding of practical challenges associated with fabrication, transportation, and erection.

The investigators met with FHWA researchers and engineers involved in the FHWA Curved Steel Bridge Research Project at the Turner-Fairbanks Highway Research Laboratory to identify areas of national need and to explore the possibility of future sponsorship. The investigators also met with prominent curved bridge researchers from several universities and companies. The “research needs” effort identified topics suitable for Masters and PhD students with interest in curved bridge stability. It also provided an understanding of potential sources of support for continuing curved bridge research.

**TASK 3. Student-oriented analytical research**

The “synthesis” and “research needs” aspects of this project identified suitable Masters and PhD topics. The analytical research effort involved graduate students who investigated curved bridge research topics that may lead to improvements in bridge design specifications or improvements in construction practice. The graduate student research topics involve steel composite construction, since that is where the primary focus of current research is directed. Both I- and box-girder cross sections were considered. The investigations were analytical in nature, rather than dependent upon laboratory testing. An MS project report and several publications were produced. Two PhD students and a MSCE student continue to work on their topics.

**TASK 4. Technology transfer**

Ultimately, success of the project depends on the dissemination of the results to stakeholders. Interaction with ALDOT, other researchers, and industry identified the need for guide documents and continuing education courses. The input from these stakeholders was used to outline a plan for future activities. Transfer of all findings to stakeholders will be facilitated through conference presentations and proceedings, journal publications, student theses and dissertations, and the final report of UTCA Project 03228.

**1.3.2 Project Team**

The research was directed by Dr. Jim Davidson, an Associate Professor in the Department of Civil and Environmental Engineering at the University of Alabama at Birmingham. Dr. Davidson was involved in the Federal Highway Administration’s “Curved Steel Bridge Research Project” (FHWA-CSBRP) while at Auburn University (1992-1996). He is currently the chairman of Task Group 14, “Horizontally Curved Girders”, of the Structural Stability Research Council and has numerous publications related to the behavior of curved bridges.

Dr. Davidson was assisted by four civil engineering graduate students: (1) Ramy Abdalla (PhD student), (2) Mahendra Madhavan (PhD student), (3) Lance Osborne (MSCE student), and (4) Toby Leamon (MSCE student). Mr. Osborne completed his MSCE requirements May 2002.
Abdalla, Madhavan, and Leamon continue to work on their degree requirements. A brief description of their stability topics and accomplishments to-date is presented in Chapter 2.

1.4 Report Content and Organization

This report provides a summary of the accomplishments of the research team and is organized into the following chapters: Chapter 1, “Introduction,” presents a general introduction, followed by a summary of the main objectives of the project. The scope of the research and project description is discussed. Chapter 2, “Accomplishments,” provides a summary of the accomplishments of the project and findings regarding research needs. Chapter 3, “Conclusions and Recommendations,” summarizes the main conclusions of this study and provides recommendations for future work.
2.0 ACCOMPLISHMENTS

2.1 Overview

This project has resulted in progress towards establishing a curved bridge stability research program within the University of Alabama System. Two PhD students and two MSCE students were recruited into the UAB graduate program as part of this project, and several papers and presentations were produced. A library of relevant papers and research reports required for a long-term graduate research program in this area was collected. The project enabled the investigators to participate in meetings and conferences focused on curved bridge stability and construction issues. An understanding of current practice and research needs, from the national and Alabama Department of Transportation perspectives, was developed. The activities of this project were divided into four distinct areas that are discussed in Section 2.2.

2.2 Stability Research Accomplishments

2.2.1 Design and Construction of Curved Box Girder Bridges

The “closed” box- or tub-girder cross section resists curvature induced torsion far more efficiently than the “open” I-girder cross section. Economic benefits of using box girder superstructures over I-girder cross sections may be substantial for sharp curvatures (radius < 1000 ft). An illustration of cross sections commonly used in curved bridge superstructures is provided in Figure 2-1.

Federally sponsored or coordinated research on box girder stability is very limited. The original scope of the FHWA Curved Steel Bridge Research Project included fundamental research on the behavior of both steel I-girder and box-girder bridges. However, soon after the initiation of the project in 1992, investigators and FHWA program managers realized that there would not be enough resources to address both I- and box-girder research. All of the box girder research tasks were subsequently eliminated. There is still a void in the understanding of curved box-girder behavior and a need to improve currently used design and construction processes. It is anticipated that a nationally sponsored large-scale project will occur in the future, after the FHWA Curved Steel Bridge Research Project is finalized.
Box girder construction practices were investigated and research needs identified. Information was collected on construction projects that involved curved box girders toward the goal of understanding the engineering and economic advantages to using closed cross section girders for curved bridges. Prominent researchers and practitioners were contacted. An understanding of construction procedures and stability issues was developed. Box girder designs were collected from other state DOTs and will be reviewed and used in analytical case studies as part of student research projects.

There are two overall aims of the box girder aspects of this project:

(1) Curved box girder bridges have not been used in Alabama but may offer economic advantages in future highway construction projects. Therefore one aim is to understand current box girder design and construction practice and how box girder geometries might help Alabama.

(2) Curved box girders were eliminated from the FHWA Curved Steel Bridge Research Project and federally organized and sponsored research projects will likely arise in the future. Therefore the second aim is to conduct preliminary work needed to be recognized as a leading research program in this area and perhaps open the door towards participation in future federally sponsored research.

Analytical stability research was initiated in this area, with a focus on the effects of distortion on the strength of curved box girders and lateral bracing requirements. Finite element models were developed. Theory-based formulations and analytical models are being developed to resolve issues associated with construction using curved box girders. The analytical research will culminate in a PhD dissertation that will address stability issues that are encountered with curved box-shaped plate girders. An ultimate goal is to develop and recommend guidelines and design criteria.
2.2.2 Stability of Curved I-Girders during Construction

Students involved in I-girder aspects of the project are developing theory-based formulations and analytical models to resolve issues associated with design and construction using curved I-girders. For example, methods used to lift single curved girders onto supports may induce significant distortion, warping, and minor axis bending stresses that were not considered in the design. It may be necessary to lift two girders temporarily braced with cross frames to provide stability during erection. Therefore, strength equations are needed for various lifting scenarios. Also, the cross frames can be subjected to significant forces during the construction of curved I-girder bridges that are not encountered in straight bridges. Engineers need design methodology for predicting bracing member forces. Transverse and longitudinal stiffeners may be required to prevent unacceptable levels of distortion, and design guidance is needed.

Current focus is on the stability of curved I-girders during construction. Curved I-girders, in particular, can be unstable during lifting and transporting unless adequately braced. Problems are common yet rarely documented. However, there are no comprehensive guidelines or recommendations on construction practices, nor is there a published survey or summary of problems encountered by DOTs during construction of curved bridges. Discussions with prominent researchers and FHWA program managers during this project indicated that this is an issue that warrants additional research.

Analytical studies have been focused on the effects of curvature-induced warping on the local buckling of curved I-girder flanges. Papers entitled “Elastic Buckling of Plates Subjected to Linearly Varying Edge Load” and “Elastic Buckling of I-Girder Flanges with a Linearly Varying Stress Distribution,” were developed. A related paper entitled “Elastic Local Buckling of Curved I-Girder Flanges” was accepted for presentation at the 2003 North American Steel Construction/Structural Stability Research Council (SSRC) Conference and will be included in the SSRC conference proceedings. A PhD dissertation is anticipated to thoroughly address stability issues that are encountered with curved I-shaped plate girders. Advanced theory and finite element methods are being used. The analytical research will culminate with improved criteria suggested for curved bridge design and construction.

2.2.3 Analysis of Single I-girders during Erection

Closed-form equations are being developed to predict maximum stresses that occur under various lifting mechanisms used during erection of curved I-girders. Support conditions that are being considered in lifting studies are illustrated in Figure 2-2. The initial phase of this research is focused on the development of equations based on small displacement torsion of thin-walled structures that represent idealized support conditions for lifting of curved I-girders. Later phases of the research will involve the use of finite element analyses to adjust the theory-based equations for deflection amplification and local stress effects.
Figure 2-2. Support conditions considered in lifting studies
2.2.4 Case Study of the I-459 Flyover

A local curved bridge construction project, the Galleria I-459 flyover in Hoover, Alabama (Figures 2-3 and 2-4), was studied from inception and preliminary design through placement of the girders and concrete deck. This study provided a better understanding of the curved I-girder bridge design and construction process. The close proximity of the project to the University of Alabama at Birmingham (UAB) and the ability to safely observe the progression of construction from the Galleria parking deck provided a unique opportunity to document the construction. Many of the persons involved in the flyover construction were interviewed, including ALDOT project managers, contractor project engineers, erectors, fabricators, and others. The fabrication company (Carolina Steel Corporation of Montgomery Alabama) was visited, engineers were interviewed, and digital images were taken to provide an understanding of problems that arise during the curving process. An understanding of challenges while transporting within the fabrication facility and from the fabrication facility to the jobsite was acquired. Erectors were interviewed to gain a practical, real-world perspective on challenges that occur at the jobsite during lifting and placing of the girders. Digital images were taken on a bi-weekly basis for several months to provide a record of the project. All of the results were merged as a comprehensive report (Osborne 2002).

Figure 2-3. Construction site of the Galleria Flyover
2.2.5 Papers, Presentations, and Reports

An important goal of the project was to disseminate the results. The following describes papers, presentations, and reports that were developed as part of this project.

Published or presented:


*Manuscript completed*

“Elastic Buckling of Plates Subjected to Linearly Varying Edge Load” Mahendrakumar Madhavan and James S. Davidson; submitted to the *International Journal of Thin-walled Structures*.

“Elastic Buckling of I-Girder Flanges with a Linearly Varying Stress Distribution,” Mahendrakumar Madhavan and James S. Davidson; to be submitted.

“Compactness Requirements for Flanges of Horizontally Curved I-Girder Bridges,” Mahendrakumar Madhavan and James S. Davidson; to be submitted.

### 2.3 Outreach and Interaction

The project facilitated valuable interaction with prominent researchers and industry leaders. The investigators met with researchers from the University of Houston, Pennsylvania State University, the University of Pittsburgh, Auburn University, and Georgia Institute of Technology. In addition to academic researchers, the investigators interacted with engineers from the FHWA Turner-Fairbanks Highway Research Center, the Pittsburgh and Tampa offices of HDR Engineering Inc., BSDI Inc., and the American Institute of Steel Construction (AISC).

#### 2.3.1 Conferences and Meetings

The following summarizes participation in conferences and meetings facilitated by the project:

- Developed and submitted white paper proposal to Dr. Bill Wright, FHWA Research Engineer, at the Turner-Fairbanks Highway Research Laboratory entitled “Guidelines for the Stability of Curved Steel Girders during Erection” (September 2001). It is essentially an offer to tackle some of the construction issues and lead an effort to develop guidelines for transporting and erecting curved steel bridges. The hope is that the white paper will initiate dialogue with Mr. Wright regarding how Dr. Davidson can assist the FHWA in this area of national need. The subject was identified as of great importance and an area that UAB could potentially contribute to in an earlier meeting with Mr. Wright.
• Participated in the Research Council for Curved Bridges (RCCB) meeting at the FHWA Turner-Fairbanks Highway Research Center, February 22 and 23, 2002. This was a working meeting of the most prominent and active curved bridge researchers. Overall activities included a review of progress and status of the FHWA-CSBRP and related efforts, detailed discussion of transitioning recent research results into guidelines and specifications, and near term plans and research needs. The meeting resulted in a lengthy list of the most pressing curved bridge research challenges.

• Participated in the North American Steel Constructors Conference (NASCC) and Structural Stability Research Council (SSRC) meeting, April 23 through 27, 2002. This included a presentation at the NASCC by Davidson entitled “Stability of Curved I-girder Web Panels.” This also included participation in other meetings such as SSRC Task Group 27 “Plate and Box Girders” and Davidson’s leadership role as the chairman of SSRC Task Group 14, “Horizontally Curved Girders.” The conference and meetings facilitated valuable interaction with prominent bridge stability researchers from around the world.

• Met with Dr. Bill Wright, Senior Research Engineer, of the FHWA Turner-Fairbanks Research Laboratory December 3, 2002. Dr. Wright is the program manager of the Curved Steel Bridge Research Project. Davidson and Madhavan gave a presentation that summarized curved bridge stability research accomplishments and activities and provided a notebook collection of related papers, manuscripts, and presentations developed by the Team.

• Participated in the Transportation Research Board (TRB) Annual Meeting, January 12-16, 2003. A technical presentation entitled “Effects of Distortion on the Strength of Curved I-Shaped Bridge Girders” hosted by TRB Committee A2C02 - Steel Bridges, in a session entitled "Analysis, Behavior, Design, and Construction of Skewed and Curved Steel Bridges" was given. The activity also included participation in the meetings of Committee A2C02, and “A2C02(1) - Subcommittee on Methods of Analyzing Steel Bridges.”

2.3.2 Curved Bridge Research Interests of the Alabama Department of Transportation

The transfer of new technologies to Alabama stakeholders can result in tax dollar savings as the region continues to populate and new bridges and highway interchanges are required. For example, curved box girder bridges are not used in Alabama, whereas other states have demonstrated substantial savings in the use of box girder superstructures for bridges with sharp curvature. Curved box girder construction introduces challenges that are different from I-girder construction, but in general, the boxes are more stable during construction and provide significantly enhanced efficiency in resisting torsional loads. Academic research can facilitate the transfer of recent advances in box girder construction to Alabama stakeholders, and can provide research-level technical expertise that can help avoid problems.

The Team met with ALDOT bridge engineers to discuss their interests and needs regarding curved bridge education and research. The following summarizes the outcome of the meeting:
Outreach and Education Needs: ALDOT expressed interest in seminars on LRFD bridge design (not specific to curved bridge design). ALDOT will have an interest in curved bridge design education as the current curved bridge research is integrated into the standard LRFD bridge specification.

Box Girder Research Interests: There are currently no box girder bridges in use or under construction in Alabama. In the past, consultants have evaluated the potential use of box-shaped superstructures instead of I-girder, but elected not to use box girders. The decision may be driven by the lack of local design firms and erection companies experienced in curved box girder construction. There will likely be several projects involving sharp curvature superstructures in the future where box girders may be considered.

Stability During Construction: ALDOT recognizes that problems commonly occur during the construction of curved I-girder bridges. However, in Alabama, all aspects of construction engineering are the responsibility of contractors. ALDOT does not have an immediate need for construction stability research. Several future construction projects, including those associated with the Highway 280/I-459 interchange and with “Corridor-X,” may offer opportunities for construction sequence investigations.

2.4 Stability Research Topics

Based upon the review of literature and interaction with industry leaders and prominent curved bridge researchers, the following were identified as discrete stability research topics in need of further investigation.

- Effects of curvature on curved I-girder flange stability, including elastic behavior, post-buckling behavior, and ultimate strength.

- Prediction of distortion induced web stresses that result from curvature for use in fatigue calculations.

- Effects of curvature on the lateral-torsional elastic buckling behavior of curved I-girders in the braced frame superstructure.

- Guidelines for deck placement sequencing to minimize construction stresses, fit-up problems, and erection stability problems for curved I-girders.

- Maximum stress predictor equations and guidelines for transporting and lifting single curved I-girders during construction.

- Simplified ultimate strength predictors for transition into LRFD format specifications.

- Requirements for transverse and longitudinal stiffener spacing and rigidity for curved plate girders based upon curvature induced distortion.
• Plate girder web panel slenderness requirements for regions of pure shear and combined bending and shear.

• Internal and external cross frame, diaphragm, and lateral bracing spacing and rigidity requirements for curved box girders, during construction and in load bearing configurations.

• Guidelines for deck placement sequencing to minimize construction stresses, fit-up problems, and stability problems for curved box girders.

• Guidelines for temporary shoring to minimize stresses, fit-up problems, and stability problems for curved box girders.

• Guidelines for transporting and erecting curved box girders.

• Equations to predict effects of distortion on the strength of curved box girders.

• Ultimate strength behavior of curved box girders.
This project resulted in progress towards establishing a curved steel bridge stability research program within The University of Alabama system. Four students were involved and produced several papers and presentations. This includes two students enrolled in the recently formed joint UAB-UAH PhD program. Papers and reports were collected that will facilitate continued research efforts. The project also facilitated interaction with prominent curved bridge researchers, state and federal government division and program managers, and industry leaders. The planning, design, fabrication, and construction of a local curved I-girder bridge flyover was studied in-depth to gain a better understanding of practical challenges associated with curved bridge design and construction. The background research and interaction with industry leaders resulted in the identification of stability research topics, and a meeting with ALDOT bridge engineers provided insight into the research and education needs and interests of Alabama.

The analytical research components of the effort can be categorized into two parts: (1) stability of curved I-girders during construction and (2) behavior and design of box girder bridges. From a national perspective, the design, fabrication, and construction of curved I-girder bridges is more mature than that of curved box girder bridges. However, significant research challenges remain for curved I-girders. The “Guide Specifications for Horizontally Curved Highway Bridges” is widely recognized to be outdated, disjointed, and difficult to use, so strength and stability research is needed to improve design formulations. Due primarily to weak torsional rigidity and a very complex distribution of stresses over the cross section, problems associated with fabricating, transporting, and erecting curved girders are more prevalent in curved I-girder construction than in straight bridge construction. Engineers not experienced in the design of curved bridge systems often make the mistake of assuming that behavior and design is the same as that for straight bridges. Instability during construction can easily translate into unsafe conditions for construction workers, not to mention unforeseen additional costs. Even though problems are common, there are no comprehensive guidelines specific to the construction of curved bridges.

The design, fabrication, and erection of curved box girders share many of the curvature-induced complications of curved I-girders. Construction using box girders often requires heavy equipment and expertise that is not locally available. However, the use of box girders for highly curved bridges offers significant cost savings, and a more attractive appearance.

There is need for research that involves partnerships of federal, state, academic, and industry to solve problems associated with the design and construction of curved bridges. Through interaction with industry leaders and leading researchers, this project identified many areas of stability research need. However, funding opportunities are limited. The Federal Highway Administration Curved Steel Bridge Project (FHWA-CSBRP) being conducted at the Turner-Fairbanks Highway Research Laboratory in McClean, Virginia, has been ongoing since 1992 and is the only large-scale federally sponsored and coordinated curved bridge project today.
Currently, FHWA is wrapping up this program and synthesizing the results. After the FHWA-CSBRP is finalized, there may be a shift in interest towards curved box girder bridge research that will offer the opportunity for researchers who are not currently sponsored. There may be other avenues for stability funding such as through the American Iron and Steel Institute (AISI), the Steel Bridge Alliance, AISC, and others. Funding from agencies such as the National Science Foundation is not likely due to the applied nature of the research.

ALDOT has not yet taken advantage of enhanced torsional resistance provided by box girders and depends on contractors to do the construction engineering of curved I-girder bridges. No severe problems have been encountered with the construction of curved bridges in Alabama. However, there are upcoming curved bridge construction projects in Alabama that will involve significant curvature and there may be future interest in sponsoring erection stability projects and projects that may look into box girder options. This may translate into opportunities for this program to assist ALDOT in the near future.

The following recommendations resulted:

- Investigate other potential sources for bridge stability research sponsorship, including AISI, the Steel Bridge Alliance, and AISC.
- Increase efforts to find graduate fellowship opportunities that can be used for stability research.
- Continue to interact with FHWA research program managers and participate in meetings of the Research Council for Curved Bridges.
- Continue to interact with ALDOT bridge engineers and to look for opportunities to assist with construction and erection studies on upcoming curved bridge construction projects.
- Continue to develop high impact papers and presentations.
4.0 REFERENCES


