DEVELOPMENT OF A SHALLOW PRESS-BRAKE FORMED TUB GIRDER FOR SHORT-SPAN STEEL BRIDGES

KARL E. BARTH

GREGORY K. MICHAELSON

MICHAEL G. BARKER

DANIEL R. SNYDER

BIOGRAPHY

Dr. Barth is the Jack H. Samples Distinguished Professor at West Virginia University. His focus is in steel bridge design, behavior, and analysis. He is a member of the AISI SMDI Steel Bridge task force and is the former chair of TRB AFF20 – Methods of Analysis of Steel Bridges and the SSRC Task Group on Plate and Box Girders.

Mr. Michaelson is a doctoral candidate and NSF GRFP recipient at West Virginia University, working under Dr. Barth. His research focus is improving the analysis and design of steel bridges.

Dr. Barker is a professor of Civil Engineering at the University of Wyoming. Dr. Barker has worked in the area of inelastic design of steel bridges, tension field action in hybrid girders, steel bridge live load serviceability and fatigue and strength behavior of high mast towers.

Mr. Snyder is the manager of business development for the Steel Market Development Institute, a business unit of the American Iron and Steel Institute. He has a bachelor's degree from Penn State and a MBA from Johns Hopkins.

SUMMARY

This paper is focused on the development of modular shallow trapezoidal boxes fabricated from cold-bent structural steel plate using standard mill plate widths and thicknesses. This concept was developed by a technical working group within the Steel Market Development Institute's (a business unit of the American Iron and Steel Institute) Short Span Steel Bridge Alliance (SSSBA), led by the current authors. This working group consists of all stakeholders in the steel bridge industry, including mills, fabricators, service centers, industry trade organizations, universities, and bridge owners. The goal was to develop innovative and economical modular solutions for the short-span steel bridge market. The proposed system meets the needs of current industry trends of accelerated bridge construction, while offering an economical solution. This paper will provide an overview of experimental testing currently being conducted and further parametric analysis and design studies focused on assessing behavior and ultimate capacity of the proposed system.

DEVELOPMENT OF A SHALLOW PRESS-BRAKE FORMED TUB GIRDER FOR SHORT-SPAN STEEL BRIDGES

Background and Scope

The Short Span Steel Bridge Alliance (SSSBA) is a group of bridge and culvert industry leaders (including steel manufacturers, fabricators, service centers, coaters, researchers, and representatives of related associations and government organizations) who have joined together to provide educational information on the design and construction of short span steel bridges in installations up to 140 feet in length. From within the SSSBA technical working group, a modular, shallow steel press-brake tub girder was developed. This girder is shown in Figure 1. This new technology consists of cold-bending standard mill plate width and thicknesses to form a trapezoidal box girder. The steel plate can either be weathering steel or galvanized steel, each an economical option. Once the plate has been press-brake formed, shear studs are then welded to the top flanges. A reinforced concrete deck is then cast on the girder in the fabrication shop and allowed to cure, becoming a composite modular unit. The composite tub girder is then shipped to the bridge site, allowing for accelerated construction and reducing traffic interruptions.

A key economic factor with this newly developed system is utilizing a press-brake to form a girder from a standard-width plate, as opposed to cutting and welding plates together to form a conventional tub girder. By employing the proposed system, the costs associated with cutting and welding of steel plates are eliminated. Furthermore, no cross-frames are needed (as the deck is cast compositely in the fabrication shop, providing continuous lateral support before the girder is erected), which again reduces the overall bridge system cost. Finally, due to the methods of fabrication, increased quality control would be gained from employing this system as the entire composite girder unit is shop-fabricated.

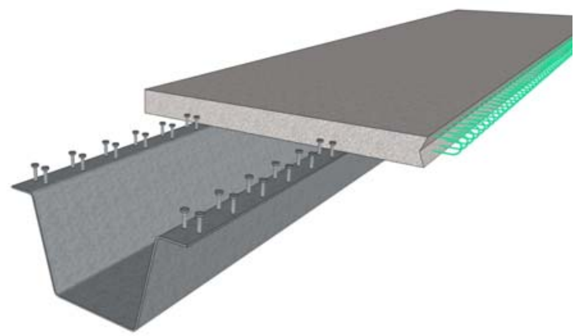


Figure 1 Conceptual Composite Press-Brake Tub Girder

Literature Review

Prefabricated steel tub-girder systems have been explored as a potential design solution for the short-span bridge market for a number of years. Many previous research efforts have shown that these types of systems have the potential to be economical and competitive in the short-span range. In recent years, the demands for accelerated bridge construction have been brought to the forefront of design. Therefore, bridge systems such as the press-brake tub girder have once again surfaced as a viable alternative to conventional bridge fabrication. Presented in this section is a comprehensive review of previous studies focused on economical and rapid bridge construction employing various shallow tub girder configurations.

Prefabricated Press-Formed Steel T-Box Girder Bridge System (1)

Taly and Gangarao (1) proposed using a press-brake to bend an A36 3/8-inch steel plate to form a tub girder in a short-span modular bridge system. At the time of publication in 1979, The American Association of State Highway and Transportation Officials (AASHTO) Specifications did not provide any criteria for the design of bridge members using a press-brake to cold form the shape of girders. Therefore, the researchers checked their tub girder design in accordance with the 1977 American Iron and Steel Institute (AISI) specifications.

In the proposed design, a prestressed concrete deck would be precast with an embedded shear stud plate, which would, in turn, be shop welded to the steel tub girder's flanges. The total width of the tub girder is 3 feet, and the total width of the prestressed concrete slab is 6 feet. This reduced size permits the complete unit to be fabricated in the shop and shipped to the construction site, greatly decreasing the amount of field labor and construction time. To account for various bridge widths, several prefabricated tub girder units are placed adjacent to one another and joined with a longitudinal closure pour. The system resists lateral loads through shear keys with weld-ties placed at the junction of the prestressed concrete slab flanges. The ends of the tub girder beams are closed off with a 3/8-inch thick steel plate diaphragm that is welded all around the perimeter of the tub girder. To provide additional support, bearing stiffeners are provided at the tub girder ends along with the 3/8-inch thick diaphragm.

In addition, Taly and Gangarao provided an alternative to the concrete-steel composite tub girder bridge system which employed an orthotropic deck. To increase the longitudinal stiffness of the orthotropic deck, WT sections would be shop welded to the steel plate deck. Like the previous design, the composite tub girder unit could be prefabricated in the shop and shipped to the construction site. The tub girder dimensions are highly dependent on the span length, ranging from a 2.5 foot to a 3.5 foot deep tub girder.

The researchers found the tub girder design with the composite concrete deck to be economical for spans of 40 to 100 feet. With the all-steel configurations, the maximum span length would be 65 feet. In addition, the authors note that the tub girders have a greater torsional stiffness then typical I-beam sections due to their closed shape. Furthermore, 95% of the total bridge system would be prefabricated and economy is achieved with the use of a press-brake to cold form the members as opposed to typical fabrication procedures for steel box girders. Also, in addition to rapid construction, the lightweight design of this system (roughly 11 tons for a 65-foot-long girder) allows for low capacity equipment for all phases of construction, including transportation and erection of the tub girders.

Composite Girders with Cold-Formed Steel U-Sections System (2)

Similar to Taly and Gangarao's proposed design, Nakamura (2) proposed a bridge system that utilizes a press-brake to cold form steel tub girders. Nakamura's bridge system includes casting a prestressed concrete slab supported by twin tub girders, forming a composite modular unit. Nakamura envisioned a continuous bridge system with multiple intermediate piers to support the superstructure. To compensate for the potential buckling of the bottom flange at pier locations, Nakamura designed the tub girders to be filled with concrete and prestressed by prestressed concrete (PC) bars, resulting in an increased strength against buckling at the support locations.

The researcher preformed several experimental bending tests on the proposed design. These tests confirmed that the tub girder behaved as a composite beam at the center of the span. Furthermore, at pier regions, the tub girder was shown to behave as a prestressed beam with the prestressed concrete preventing local buckling of the bottom flange. Finally, Nakamura concluded that this bridge system would in fact be practical and feasible since it has adequate bending strength and deformation capacity. A drawback to Nakamura's design is that the tub girders require more steel than conventional plate girders. However, the cost is offset by decreased fabrication costs, thereby resulting in an economical design.

Con-Struct Prefabricated Bridge System (3)

Nelson Engineering Services has developed a cold-formed tub girder bridge system similar to previous designs mentioned above (3). This system, Con-Struct, incorporates a prefabricated composite bridge girder consisting of a shallow steel tub girder and a concrete deck. To increase the service capacity of this system, the steel tub girders are stressed into a camber, and the concrete deck is cast onto the girders in their stressed state. Once the concrete is cured, the steel compressive stress is locked in to provide camber and increase the service capacity of the structure. Employing this system, designs are valid for spans up to 60 feet (according to AASHTO LRFD Specifications)

Folded Plate Girders (Developed at the University of Nebraska) System (4)

The University of Nebraska, Lincoln has also researched cold-bent steel tub girders and developed a composite steel girder system utilizing folded plate girders (4) (5). This system utilizes an inverted tub girder where the flanges of the girder are bent inwards. The concrete deck is then cast on the wider center flange as opposed to previously developed systems, where the deck is cast on the two smaller exterior flanges. An advantage of this system is that the orientation of the girder allows maintenance and ease of inspection of the folded plate girder. Also, the wider top flange resulting from the girder orientation provides a safe work area for construction personal.

TxDOT Rapid Economical Bridge Replacement System (5)

In an effort by the Texas Department of Transportation (TxDOT) to create a more shallow bridge superstructure, a bridge system consisting of a shallow steel tub girder was developed (6). Specifically, the solution was to use a tub girder that consisted of a 5-foot-wide bottom flange width and a 3-foot-deep web. Two rows of shear studs were welded to each top flange, and a reinforced concrete deck was cast.

An application of this concept was completed in August of 2010. The bridge consisted of four simply supported spans of 45 feet, 100 feet, 100 feet, and 65 feet, respectively. The total width of the bridge was 78 feet; as a result, six tub girders were utilized. It should be noted that, in this system, while accelerated bridge construction methods were used, conventionally-fabricated steel tub girders (as opposed to girders formed using cold bending) were employed.

MDOT Prefabricated Steel Box-Girder Systems (6)

The Michigan Department of Transportation (MDOT) recognized the need for a prefabricated bridge system to be shipped to the construction site where only placement and post-tensioning were required (7). The goal was to create an entirely prefabricated composite bridge which would eliminate the need for lengthy and costly road closures for short-span bridges. In order to accomplish this, a research project was conducted on a shallow, cold-bent tub girder system utilizing a prestressed concrete deck. Specifically, this project focused on the design of individual units which would be joined with longitudinal deck pours. Experimental testing coupled with finite element analyses demonstrated that this system would be competitive in the short-span bridge market.

Conclusions

Several researchers over multiple decades have researched the potential economy of prefabricated bridge systems incorporating shallow steel tub girders. Many researchers have found these technologies to be competitive in the short-span bridge market. However, while many of the research conclusions regarding the efficiency and economy of these systems have been promising, many of the systems were hindered by somewhat complex fabricated elements, which would increase the total system cost. In addition, many of these systems did not have industry-wide support, which resulted in their lack of use in mainstream construction of short-span bridges. Therefore, a modular tub girder with simplified details, supported by all levels of the bridge industry, would present a competitive solution for short-span bridges.

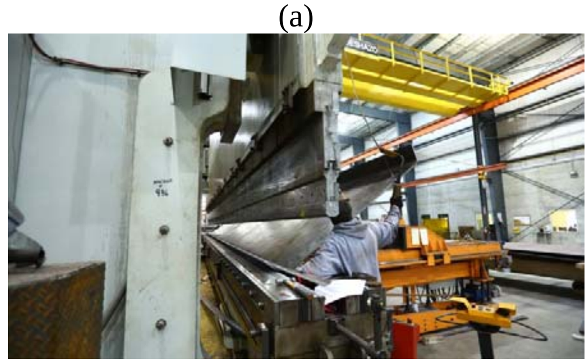
Development of Proposed System

Background

Accelerated bridge design and construction are areas of high importance to bridge owners due to the potential for fast, efficient, and economical bridge solutions. As a result, the bridge industry is quickly moving towards prefabricated bridges as the preferred method of bridge construction due to the increased quality control associated with prefabrication and the speed at which prefabricated bridges can be erected (resulting in reduced traffic interruptions, improved construction zone safety, decreased environmental disruptions, and improved life cycle costs).

In October of 2011, a retreat with key steel industry stakeholders was held in Chicago, IL with the intent to develop innovative and economical modular solutions for the short-span steel bridge market. Several solutions were developed from this meeting with a focus on press-brake tub girders. The development of the press-brake tub girder was originated at this retreat by a technical working group within the Short Span Steel Bridge Alliance (SSSBA), led by the authors.

(a)



(b)

Figure 2 Forming of a Press-Brake Tub Girder (a) large-capacity press-brake, (b) bending of specimen’s top flange.

Utilizing a standard plate width, tub girders are fabricated using a large capacity press-brake. Plates are aligned in the press-brake, and cold bent to achieve target bend radii.

Using this girder configuration and method of fabrication, press-brake tub girders can be fabricated in under an hour. Figure 2 shows a large capacity press-brake being used to form one of the girders used for testing (see Section 4).

Preliminary Design of Press-Brake Tub Girders

Current AASHTO provisions are not specifically applicable to the design of cold-bent tub girders (8). Therefore, preliminary specimen design was completed in two stages. First, a spreadsheet was developed to compute the section properties of any configuration of tub girder. Next, design iterations were performed based on conservative estimates of press-brake tub girder capacity (essentially, limiting the capacity of the composite girders to the yield moment) to assess their validity for the short-span bridge market. For this effort, two different plate thicknesses were evaluated (7/16" and 1/2") and three different standard mill plate widths were evaluated (72", 84" and 96"). For each variation, a design study was performed by investigating different variations of the girder dimensions in order to obtain an optimum girder configuration. For this study, the slope of the webs was kept at a constant 1:4 slope, and the inside bend radii of the girders was kept at a constant value of five times the respective plate thickness. Figure 3 presents the results of these studies on an 84" × 7/16" plate. The optimum section, in this case the highest yield moment, using an 84" × 7/16" plate was found to have a top flange width of 6 inches and a total girder depth of 23 inches.

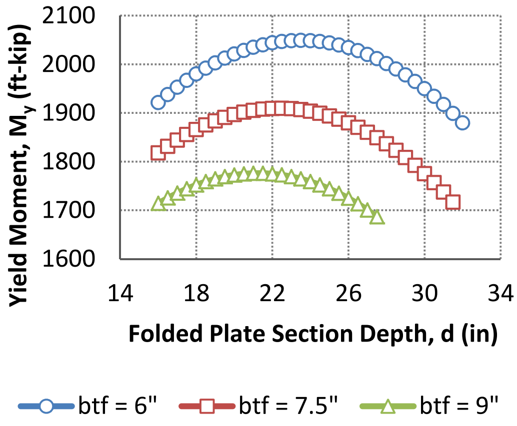


Figure 3 Preliminary Design Comparisons for an 84" × 7/16" Standard Mill Plate

Preliminary Design Results

As previously stated, since current AASHTO provisions are not specifically applicable to cold-bent tub girders, the girders in this study were sized based on a conservative estimate of flexural capacity. For each of the aforementioned variations of plate widths and thickness, a design evaluation was performed by computing moments according to AASHTO Strength I and Service II load combinations for span lengths in 5-foot increments. These were then plotted to determine the section's validity under different span length requirements. Figure 4 shows one of these plots for a 96" × 1/2" plate. As shown, according to conservative assumptions of capacity, this technology would be viable for spans up to 60 feet.

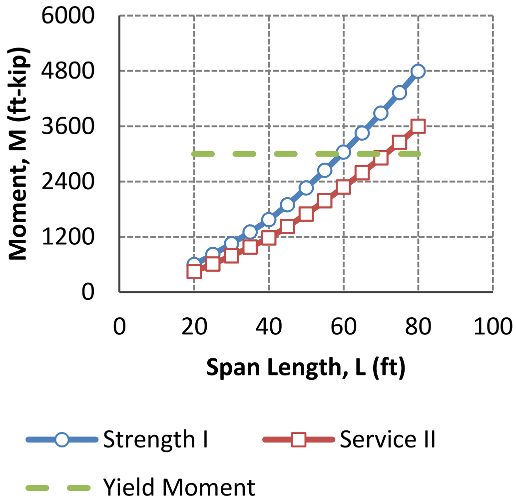


Figure 4 Design Evaluations for a Press-Brake Tub Girder (96” × 1/2” Standard Mill Plate)

Experimental Testing Program

Background

In order to verify the performance and capacity of this newly-developed modular tub girder, physical flexural testing is currently being conducted at the Major Units Laboratory at West Virginia University. For the experimental testing program, plate samples were donated by several North American Plate producers which include Nucor-Yamato Steel, SSAB Americas, Evraz North America, and US Steel. Current testing focuses on evaluating the capacity of the composite and non-composite system along with evaluation of both fatigue and modular system performance. Specimens for current testing were cold-bent using a commercial press-brake. Shear studs and bearing plates were then welded to the tub girders before shipping them to the Major Units Structures Lab at West Virginia University. The specimens will be testing using a 330-kip MTS servo-hydraulic actuator (see Figure 5).

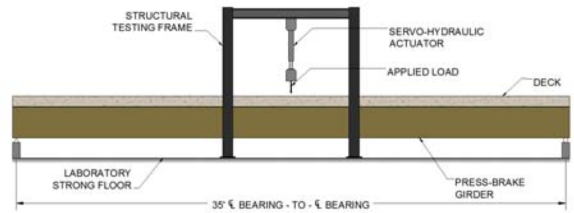


Figure 5 Typical Test Setup

Specimen Design

As shown previously (see Figure 3), the optimum section using an 84” × 7/16” plate was found to have a top flange width of 6 inches and a total girder depth of 23 inches. Figure 6 shows a cross-section view of the press-brake tub girder that will be used for experimental testing. It should be noted that three of tests will be completed using 60” wide strip mill plate specimens and this geometry is not shown here. For the 84” wide specimens, two rows of 7/8” x 4” shear studs are placed on each top flange. End bearing plates are also utilized to prevent potential premature bearing failure during flexural testing (see Figure 7). A reinforced concrete deck will also be cast on the top flanges as shown (Figure 8).

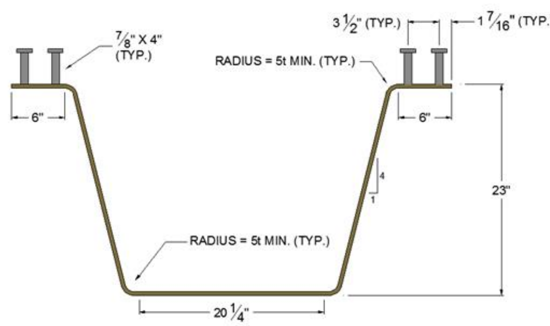


Figure 6 Testing Specimen Dimensions

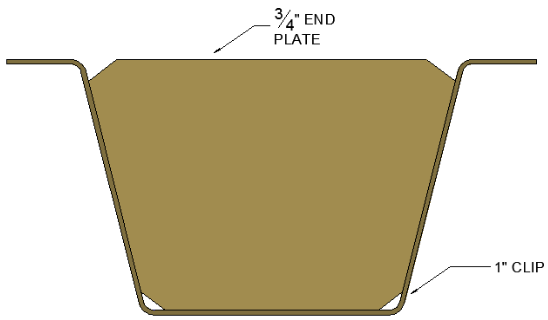


Figure 7 Tub Girder Bearing Plate

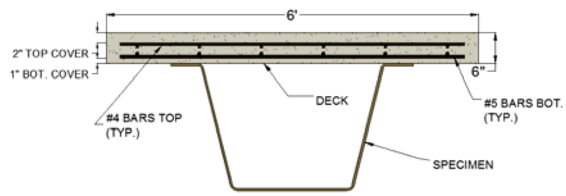


Figure 8 Deck Design for Composite Girder Specimen

Current Testing Results

Flexural testing of Specimen One has been completed at West Virginia University. As previously stated, this specimen was loaded to failure at a relatively monotonic rate to simulate static load conditions. Figure 9 shows the load-deflection curve resulting from experimental testing of this specimen.

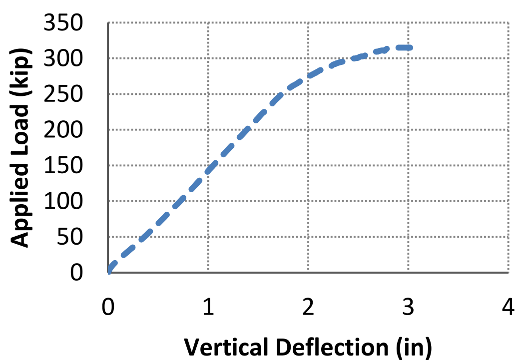


Figure 9 Load-Deflection Response of Specimen One

FEA Procedures

In addition to physical testing of the press-brake tub girders, parametric studies will be conducted to assess design performance using a refined three-dimensional finite element modeling technique. Modeling will be conducted using the commercial finite element software package Abaqus/CAE (9). Modeling results will be benchmarked against experimental data to assess their validity and accuracy.

Modeling Procedures

Element selection for these models included general purpose shells with reduced integration and hourglass control. The tub girder and concrete deck were modeled using four-noded shell elements. The bearing plates, due to their geometry, were modeled with both four-noded and three-noded shell elements. In order to simulate composite action between the concrete deck and the press-brake tub girder, node to node multi-point constraints were used, which restrict the degree of freedom between the selected nodes. Boundary conditions in the finite element model simulated a simply-supported beam (hinge-roller) condition. Figure 10 illustrates a finite element mesh of a press-brake tub girder composite specimen.

Figure 10 Finite Element Model of Composite Press-Brake Tub Girder Specimen

The tub girders in this study are comprised of HPS-50W weathering steel, and modeled using an elastic-plastic constitutive law including strain hardening effects. Concrete with a compressive strength of 4 ksi was employed for the deck and was modeled utilizing a concrete damaged plasticity model available in Abaqus which assumes that the two main failure mechanisms are tensile cracking and compressive crushing of the concrete.

Modeling Results

As previously stated, flexural testing of Specimen One has been completed at West Virginia University. Figure 11 shows a comparison between experimental results and those obtained from the previously described finite element analysis procedures. As shown, the modeling technique correlates quite well with experimental results.

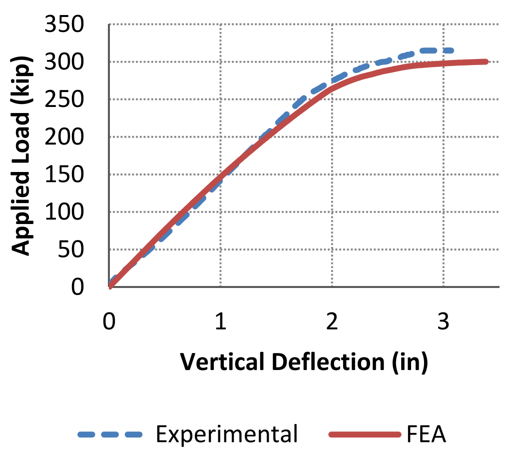


Figure 11 Comparisons with Experimental and Analytical Results

Strain Compatibility Assessment

To assess the flexural capacity of press-brake tub girders, a strain compatibility based analysis procedure was developed. The results of this assessment are used to determine a reasonable estimate of ultimate flexural capacity for design purposes. Subsequent verification of this procedure is through refined FEA modeling as previously discussed.

Using the mechanistic strain compatibility procedure, it was possible to determine the ultimate flexural capacity of a given cross-section defined by geometric and material properties. By assuming the ratio M_{DL}/M_y = 0.50 (10), the dead load moment acting on the non-composite steel girder (M_{DL}) could be determined as 50% of the non-composite yield moment (M_y). Assuming this ratio allowed for the dead load effects to be accounted for in the compatibility analyses.

By assuming a concrete strain of 0.003 at crushing and a linear strain distribution, the ultimate capacity of a typical composite press-brake tub girder girder in positive flexure can be predicted. To begin the analysis, an assumed value to the depth of the neutral axis was chosen. Using a linear strain distribution and superimposing the strains induced by dead load effects on the non-composite steel girder, the final strain profile was determined.

Concrete in compression was assumed to reach a stress equal to 0.85 times the compressive strength, f_c' whereas concrete in tension was assumed ineffective. The stresses in steel elements were assumed to be the minimum of E (29000 ksi) times the strain or the yield stress, F_y. The depth of the neutral axis was then iterated such that is resulted in a net sum of zero force in the cross-section. The stresses along the cross-section were then integrated to obtain the nominal capacity of the cross-section.

Figure 12 shows a comparison of the analytical and strain-compatibility results. As shown, the strain compatibility analysis proves quite well in predicting the ultimate capacity of the composite press-brake tub girder specimen. Using this procedure, an updated estimate of capacity was obtained for the design studies discussed previously. Figure 13 shows an updated plot of the design evaluation in Figure 4. As shown, using more accurate estimates of girder capacity, this technology would be viable for spans up to 75 feet or higher.

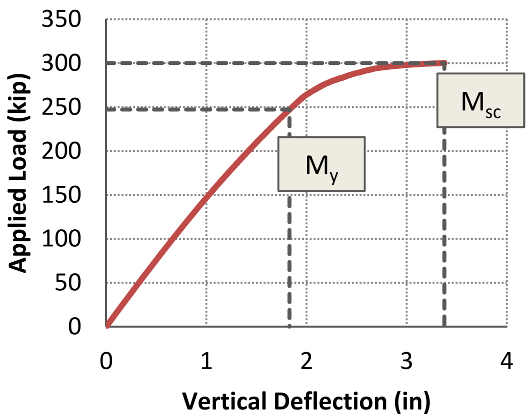


Figure 12 Comparisons with Analytical and Strain Compatibility Results

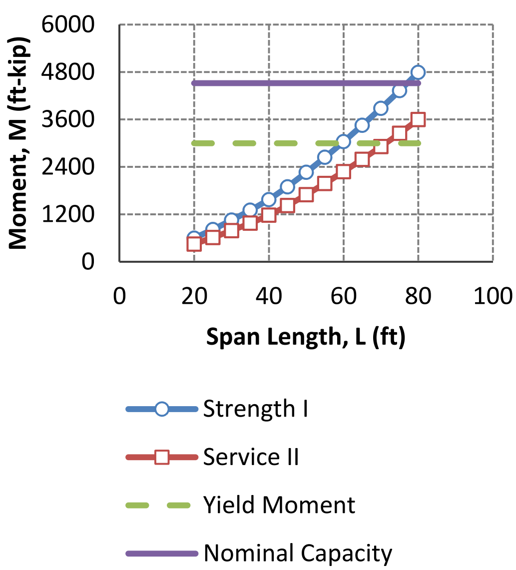


Figure 13 Updated Design Evaluations (96” × 1/2” Standard Mill Plate)

Summary and Conclusions

This paper is focused on the development of shallow steel press-brake tub girders to provide an economical steel solution for short-span bridges. Previous research has shown that systems utilizing cold-bent steel tub girders and/or accelerated bridge construction techniques can be competitive and economical in the short-span range. An added benefit of the system proposed by the authors is the use of simplified details and industry support within the SSSBA technical working group.

Preliminary design calculations coupled with experimental testing, refined three-dimensional finite element analyses, and strain compatibility assessments have shown the proposed design to be a practical solution for moderate spans in the short-span range. Current testing at West Virginia University will be used to accurately assess design performance and capacity of this newly-developed modular system. In addition, parametric finite element studies will be performed to further validate design performance and improve capacity predictions.

References

1. Taly, N. & Gangarao H. 1979. *Prefabricated Press-Formed Steel T-box Girder Bridge System*. Engineering Journal/America Institute of Steel Construction: 75-83.
2. Nakamura, S. 2002. *Bending Behavior of Composite Girders with Cold Formed Steel U-Section*. Journal of Structural Engineering: 1169-1179.
3. Tricon Precast, 2008. *Con-Struct Prefabricated Bridge System*. Standard plans. Tricon Engineering Group, Ltd.
4. Burner, K. 2010. *Experimental Investigation of Folded Plate Girders and Slab Joints Used in Modular Construction*. Civil Engineering Thesis, University of Nebraska Lincoln.
5. Glaser, L. 2010. *Constructability Testing of Folded Plate Girders*. Civil Engineering Thesis, University of Nebraska Lincoln.
6. Chandar, G., Hyzak, M. & Wolf, L. 2010. *Rapid, Economical Bridge Replacement*. Modern Steel Construction.
7. Burgueño, R. & Pavlich, B. 2008. *Evaluation of Prefabricated Composite Steel Box Girder Systems for Rapid Bridge Construction*. Department of Civil & Environmental Engineering, Michigan State University.
8. American Association of State Highway and Transportation Officials. 2010. *AASHTO LRFD Bridge Design Specifications, 5th Edition*. Washington, DC: AASHTO.
9. Dassault Systèmes. 2009. *Abaqus/CAE Users Manual (Version 6.9)*. Providence, RI: Dassault Systèmes Simulia Corp.
10. Roberts, N. 2004. *Evaluation of the Ductility of Composite Steel I-girders in Positive Bending*. Civil and Environmental Engineering Thesis, West Virginia University.