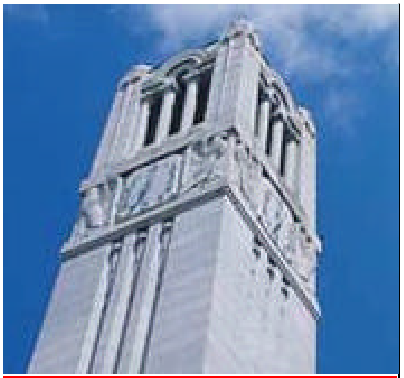

NC STATE UNIVERSITY

Constructed Facilities Laboratory
Department of Civil, Construction, and Environmental Engineering

Research Report
No. RD-06-04

FHWA/NC/2006-22

REVIEW OF NCDOT PRACTICES FOR ANALYZING OVERHANG FALSEWORK

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Prepared for:

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Research and Analysis Group
Raney Building
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September 2006

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16. Abstract

The proper design and detailing of bridge overhang falsework is an important part of the bridge construction process. Improper analysis and design of the falsework system can result in complete falsework system failure, excessive overhang formwork deflections and high locked-in lateral bending stresses in the supporting girders. This could lead to unexpected construction expenses and long construction delays. In an effort to avoid potentially serious problems with the overhang falsework, the North Carolina Department of Transportation (NCDOT) provides an extensive review of the detailed drawings and calculations submitted for each bridge project. In an effort by the NCDOT to produce standardized details for bridge overhang falsework, a need to review the current analysis and design procedures adopted by the department was identified. The objective of this research project was to provide an independent review to ensure that the analysis procedures and the design assumptions integrated into the current guidelines are in compliance with basic engineering principles and the latest ACI and AASHTO specifications. Discussions with design consultants and contractors were included as a part of the independent review. To assist with the independent review a spreadsheet program for the analysis and design of overhang falsework systems was developed utilizing the current NCDOT design and analysis provisions. It was concluded that the NCDOT analysis and design guidelines were in compliance with basic engineering principles and the current ACI and AASHTO design specifications. Additional observations, recommendations and conclusions were developed as a part of this study and are included within this report.

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Executive Summary

The proper design and detailing of bridge overhang falsework is an important part of the bridge construction process. Improper analysis and design of the falsework system can result in complete falsework system failure, excessive overhang formwork deflections and high locked-in lateral bending stresses in the supporting girders. This could lead to unexpected construction expenses and long construction delays. In an effort to avoid potentially serious problems with the overhang falsework, the North Carolina Department of Transportation (NCDOT) provides an extensive review of the detailed drawings and calculations submitted for each bridge project. In an effort by the NCDOT to produce standardized details for bridge overhang falsework, a need to review the current analysis and design procedures adopted by the department was identified. The objective of this research project was to provide an independent review to ensure that the analysis procedures and the design assumptions integrated into the current guidelines are in compliance with basic engineering principles and the latest ACI and AASHTO specifications. Discussions with design consultants and contractors were included as a part of the independent review. To assist with the independent review a spreadsheet program for the analysis and design of overhang falsework systems was developed utilizing the current NCDOT design and analysis provisions. It was concluded that the NCDOT analysis and design guidelines were in compliance with basic engineering principles and the current ACI and AASHTO design specifications. Additional observations, recommendations and conclusions were developed as a part of this study and are included within this report.

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REVIEW OF NCDOT PRACTICES FOR ANALYZING OVERHANG FLASEWORK

1.0 Introduction

1.1 Background

The proper analysis and design of bridge deck overhang falsework systems is an important part of the construction process. The primary concern is the safety of the construction workers and other personnel in the construction area. A falsework failure can result in loss of life, long construction delays, extensive property damage, and considerable liability expenses. Improper analysis and design of the falsework system can result in complete system failure, excessive overhang formwork deflections and high locked-in lateral bending stresses in the supporting girders.

Overhang falsework is used to support the formwork needed to cast the overhang of the concrete bridge deck. The weight of the wet concrete, deck screed, construction workers, and the formwork itself creates forces within the falsework that must be supported by the exterior bridge girders. These vertical and torsional forces from the falsework are transferred directly to the exterior girder (see Figure 1). Proper analysis of the falsework system is required to determine the actual loads that will be transferred to the supporting girder. Careful consideration of the maximum allowable load, torsion and deflections is of great importance.

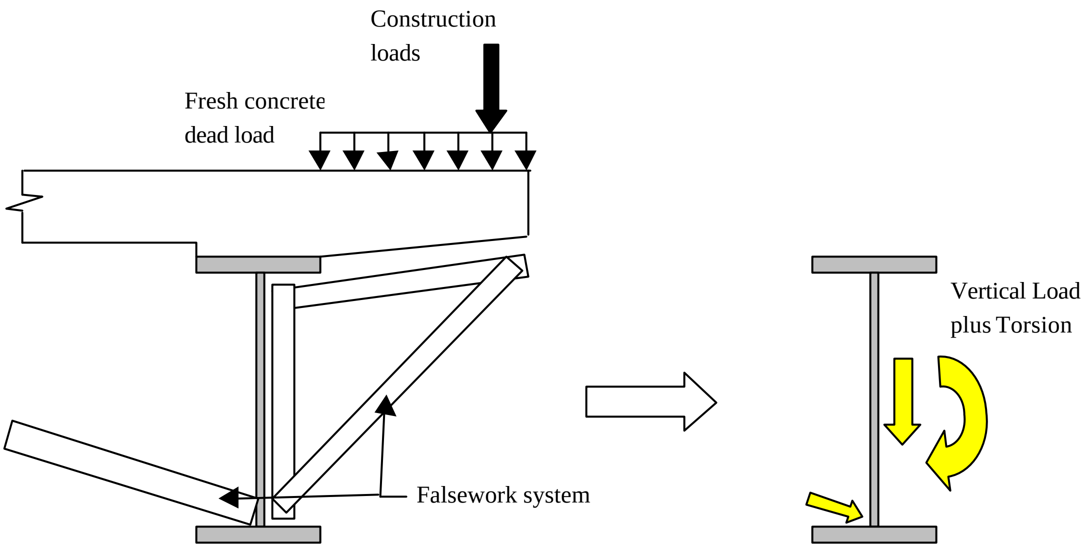


Figure 1. Generalized forces transferred from the falsework to the supporting girder

There a numerous publications related to the design of formwork for construction of concrete slabs. For purposes of this research project, the design specifications and related publications by AASHTO and ACI are most relevant. The three AASHTO publications that will be utilized are as follows: *Guide Design Specifications for Bridge Temporary Works* (AASHTO, 1995a), *Construction Handbook for Bridge Temporary Works* (AASHTO, 1995b), and *Standard Specifications for Highway Bridges, Seventeenth Edition* (AASHTO, 2002). The three ACI publications that will be utilized are as follows: *347R-01: Guide to Formwork for Concrete* (ACI, 2001), 3*45R-91: Guide for Concrete Highway Bridge Deck Construction* (ACI, 1991), and *ACI SP-4, Formwork for Concrete, 6th Edition* (Hurd, 1995). These six publications provide comprehensive guidelines on the analysis and design of bridge deck formwork systems. In addition, a number of state DOT's have developed their own standard details and specifications, which have been reviewed as part of this project.

1.2 Problem Definition

In an effort to avoid potentially serious problems with the overhang falsework, the NCDOT provides an extensive review of the detailed drawings and calculations submitted for each bridge project. This is a time consuming process for the NCDOT personnel that is further augmented by the need for revisions and resubmittal of the drawings and design calculations. The need to revise and resubmit the falsework drawings and calculations can result in construction delays and additional costs for the contractor. In past years, some contractors have argued that the NCDOT falsework requirements are overly restrictive and as a result, have submitted damage claims to recover the additional cost.

Some state transportation departments have developed extensive guidelines and standardized details for bridge falsework systems. The use of standard details generally reduces the effort required the DOT during the review process, and reduces the uncertainty and risk assumed by the contractor. The reduced uncertainty and risk, associated with the falsework submittal, should result in lower construction costs and higher safety levels for the bridge deck construction.

An effort by the NCDOT to produce standardized details for bridge overhang falsework has identified a need to review the current analysis and design procedures adopted by the department. The review is necessary to ensure that the analysis procedures and the design assumptions integrated into the current guidelines are not too restrictive and that they are in compliance with the latest ACI and AASHTO specifications.

1.3 Research Objective

The primary objective of this research project was to provide an independent review of the current procedures used by the NCDOT to analyze bridge deck overhang falsework and to evaluate the appropriateness of the NCDOT design assumptions.

1.4 Outline of Report

This report consists of 3 primary sections outlined as follows:

- Section 2 provides a summary of the independent review process of the current falsework practices.
- Section 3 provides details of development of an excel program that performs the necessary calculations to design and analyze overhang falsework systems.
- Section 4 provides a summary of the recommendations and conclusions.

2.0 Review of Current Practices

2.1 Evaluation Procedure

The overall plan of work to conduct the evaluation of the falsework analysis procedures was divided into three primary tasks. Details of each task are as follows.

2.1.1 Task 1 – Data Gathering and Discussions with NCDOT personnel

The first stage of the review process was to discuss the primary assumptions and design methodology with the NCDOT personnel. The particular concerns, expressed by some of the contractors, with regards to the restrictiveness of the falsework requirements were discussed. This was the beginning of an ongoing dialogue between the research team and the NCDOT personnel.

2.1.2 Task 2 – Independent review of design guidelines

An independent review of the current NCDOT falsework analysis and design provisions was performed by each of the research team members. The design methodology was investigated to determine the adequacy of the design loading, allowable deflections, and allowable girder loads. Careful consideration was given to the evaluation of all assumptions made within the procedure. The procedures were for compliance with structural engineering principles and the applicable ACI and AASHTO specifications. The NCDOT procedures were also compared to the procedures followed by other DOT's within the geographic region.

2.1.3 Task 3 – Development of Falsework Evaluation program

To facilitate the development of standard details and to simplify the falsework evaluation process by NCDOT, a Microsoft Excel program was developed. The program utilizes the current NCDOT falsework design guidelines and assumptions. The development and instructions for use of the program are included in Section 3 of this report.

2.1.4 Task 4 – Development of final recommendations and conclusions

The results from the first three tasks were compiled to develop the final recommendations. The resulting recommendations and conclusions are presented in section 4 of this report.

2.2 Summary of Current NCDOT Falsework Review Procedures

The current falsework submittal review guidelines are presented within this section. Each of these guidelines investigated to by the research team to understand the origin of the requirement and the methodology utilized.

2.2.1 GENERAL

1. Deck slab falsework and formwork shall comply with NCDOT Project Special Provisions and Standard Specification sections 420-3 and 420-15. Other references listed at the end of this section may be used in review performance checks.

2. Check for Project Special Provision requirement of falsework design by North Carolina Registered Professional Engineer when falsework and forms are over or adjacent to traffic.

3. Advise the Prestress Concrete Engineer of Materials and Tests Unit of the approved hanger insert spacing on precast prestressed concrete girders in cases where hardware is placed in casting yard.

2.2.2 CHECK COMPLETENESS AND CORRECTNESS OF SUBMITTED INFORMATION

For checking deck slab falsework, the following information is required:

1. Screed type and model, screed weight, weight distribution to each rail, wheel configuration, wheel spacing and maximum wheel load.

Ensure that the size and weight of the transverse screed is compatible with the skew bridge width. Transverse screeds used on spans with the skew angles less than 75° or more than 105° shall be oriented and operated parallel to the skew.

Use of longitudinal screed shall be generally limited to pours of 85 ft. or less in length.

2. Screed support details.

3. Overhang bracket manufacturer, type, load capacity, bracket spacing. Ensure that the bracket can fit between the girder flanges and has enough adjustability.

4. Hanger manufacturer, type, load capacity, spacing and connection details.

5. Size, spacing, species and grade of timber used.

6. Formwork and falsework details for stage construction including closure pours.

7. For non-proprietary systems such as needle beams or custom-made brackets: details of member sizes, connections, load capacity and spacing of hangers and jacks are required.

2.2.3 MINIMUM DESIGN LIVE LOADS

Deck slab formwork…………………………….50 psf

Deck slab falsework…………………………..20 psf applied over the area supported
+ 75 plf applied at the outside edge
of deck overhangs

Screed Load…………………………………..load configuration and distribution
*per manufacturer's catalog

Any other known construction equipment

* If load distribution data cannot be obtained, then assume about 65% of total screed load is carried by one screed rail.

2.2.4 PERFORMANCE CHECKS FOR BRIDGE DECK SLAB OVERHANG FALSEWORK ON STEEL GIRDERS OR ROLLED BEAMS

1. When using bracket type overhang falsework, the bracket heel pushing against the girder web could cause it to deflect excessively. This could result in an objectionable deflection of the deck overhang and a scalloped overhang appearance between permanent diaphragms. To prevent this, the vertical deflection at edge of overhang slab due to dead loads shall not exceed ¼".

2. To limit vertical deflection at the edge of overhang (referenced above) to ¼", provide a full height vertical timber not less than 4" thick between the bracket heel and the girder web.

3. Locked-in lateral bending stress in the girder top flange due to torsional effect of bracket type falsework overhang dead loads shall not exceed 2.0 ksi. (Screed weight and construction live load may be neglected for this check.)

4. Ensure that the steel diaphragms at bents and at intermediate locations are deep enough and effective in providing the required torsional restraint. If any diaphragm is considered inadequate, then provide two #5 tie bars, each bar welded to a row of shear studs on girders in the exterior bay.

5. Provide additional temporary torsional bracing between permanent cross-frames and K-frames to keep the locked-in girder stress within the limit stated in item number 3 above.

6. The controlling criterion in determining the allowable load in the tie bars is the bending strength of the shear studs. The load per #5 tie-bar welded to a row of three shear studs should not exceed 2.0 kips.

7. Welding hangers directly to girder tension flange is not permitted.

8. Check adequacy of brackets, hangers and timber forms for possible maximum imposed loading.

9. Needle beams are usually not allowed, but due to torsional weakness of shallow rolled beams, use of needle beams on shallow 27" rolled steel beams with greater than 36" overhang width is required. Check the deflections of the exterior beam and the next interior beams and ensure that the differential value is not excessive.

10. Check overall stability of the overhang falsework system, especially for needle beams and for unusual situations.

2.2.5 PERFORMANCE CHECKS FOR BRIDGE DECK SLAB OVERHANG FALSEWORK ON PRECAST PRESTRESSED CONCRETE GIRDERS

1. Locked-in torsional stress in precast prestressed concrete girders shall not exceed one quarter of girder cracking torque for dead loads, and one half of girder cracking torque for sum of dead and live loads. Cracking torque values of precast prestressed concrete girders shall be taken as follows in accordance with ACI 1995:

Girder Type	Cracking torque values	
	f'c = 5,000 psi	f'c = 8,000 psi
AASHTO TYPE II (36")	53,100 lb. ft.	71,800 lb. ft.
AASHTO TYPE III (45")	96,800 lb. ft.	131,100 lb. ft.
AASHTO TYPE IV (54")	159,600 lb. ft.	216,000 lb. ft.
AASHTO TYPE V (63")	191,800 lb. ft.	259,600 lb. ft.
AASHTO TYPE VI (72")	204,000 lb. ft.	276,100 lb. ft.

2. Ensure intermediate and bent concrete diaphragms are adequate to provide required torsional restraint. At each permanent concrete diaphragm provide minimum two #5 tie bars welded to girder stirrups in exterior bay. For tie bars, assume following allowable capacities:

   Allowable load in a #5 Tie Bar welded to a girder #4 stirrup (10" H x 6" W) braced with a 1/4" steel plate welded 3" to each stirrup leg is 5.0 kips (based on allowable rebar stress = 0.7 Fy = 0.7 x 60 = 42 ksi).

3. If loads carried by tie bars above concrete diaphragms are exceeded, then provide additional torsional bracing between the diaphragms. This bracing shall consist of tie bars welded to girder stirrups and timber struts placed diagonally in exterior bay.

4. Check the adequacy of the diagonal timber struts.

5. Check the adequacy of formwork, bracket, hanger, and connections for maximum loading. For welds, assume following allowable capacities using E70XX electrode:

   .375" hanger strut welded to #4 stirrup leg…….1250 lbs/weld point
   .444" hanger strut welded to #4 stirrup leg…….1475 lbs/weld point

6. Check overall stability of falsework, especially for unusual situations.

2.2.6 Miscellaneous

1. Timber overhang brackets are not considered readily adjustable and are not permitted generally, except for on very narrow overhangs.

2.3 Need for Standardization of Details

Throughout the independent review process, it was apparent that the need for standardized falsework details was significant. The falsework analysis and design process is iterative and requires a significant engineering effort to properly design and detail all of the components. In an effort to simplify this process for the NCDOT, the Falsework Analysis program was developed by the research team. The program utilizes the current practices for design and analysis utilized by the NCDOT. The details of the program are presented in section 3 of this report.

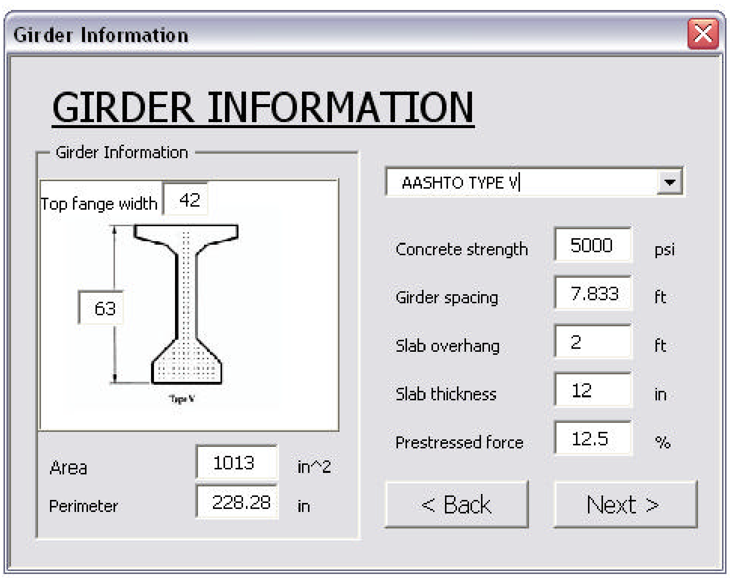
3.0 Falsework Analysis Program

3.1 Overview

A spreadsheet program named OVERHANG FALSEWORK was developed to calculate the maximum bracket spacing for bridge deck overhang construction. The program was developed using Microsoft Excel with Visual Basic. The program calculates the appropriate limit states in accordance with ACI and AASHTO codes and the results from each code are presented in the output. To find the maximum bracket spacing, the formwork and falsework properties are taken into account. This program finds the maximum bracket spacing considering the strength of the girder, hanger, bracket, formwork joists. This allows the designer to adjust design parameters easily. The procedure is described in detail in the following sections.

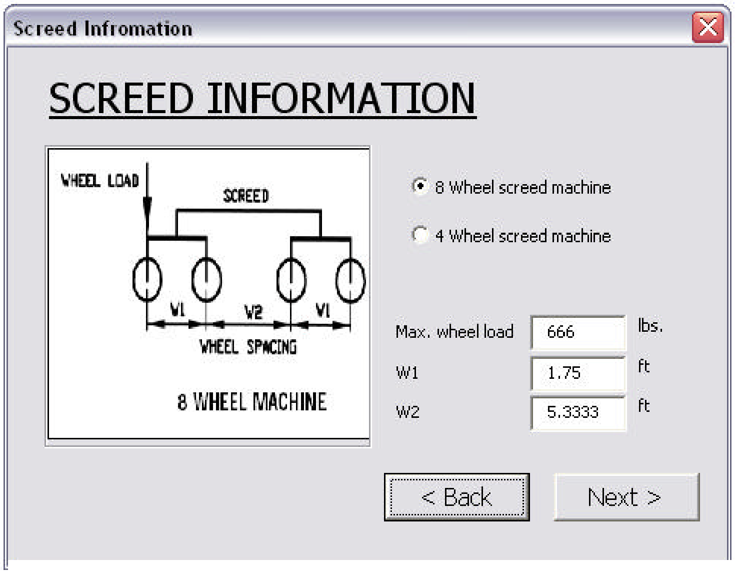
3.2 Required Program Input

Dialog boxes have been provided in the program for the user to input the necessary data required to calculate the restraint program. The dialog boxes are self explanatory and provide the user with default values from the previous run. The units for the input data are also indicated in the dialog boxes. The default typical AASHTO girder information is provided and a custom section can be used if needed. The input is separated into five categories: girder, screed, bracket, formwork, and strut. The inputs are the geometry and material properties. Inputs will be stored only when a user clicks “Next >”. Screen shots of the dialog boxes and a description of the required input is presented herein.



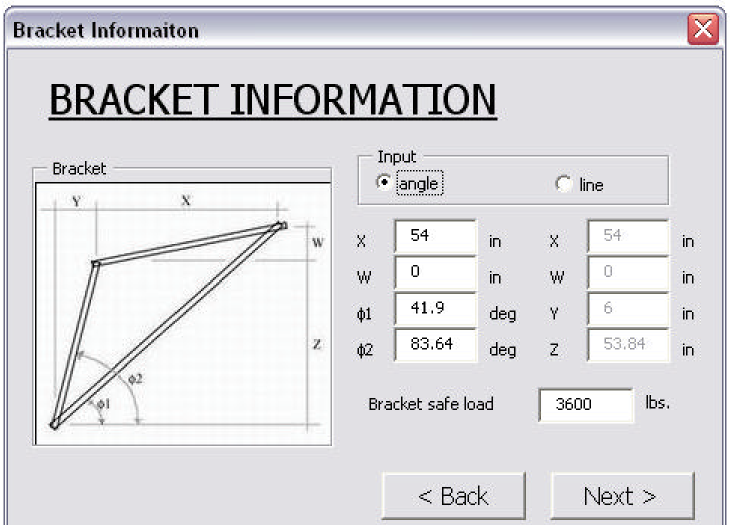
<u>Girder information</u>

1. Select type of girder: AASHTO Type II-VI, Bulb-tee, or steel girder
2. Strength of concrete
3. Girder spacing
4. Slab overhang and thickness



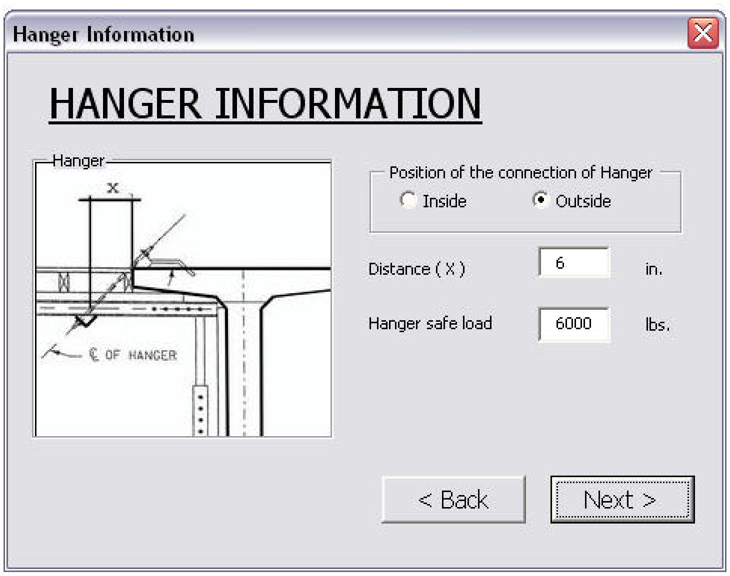
Screed information

User can choose screed type; 8 wheel or 4 wheel.



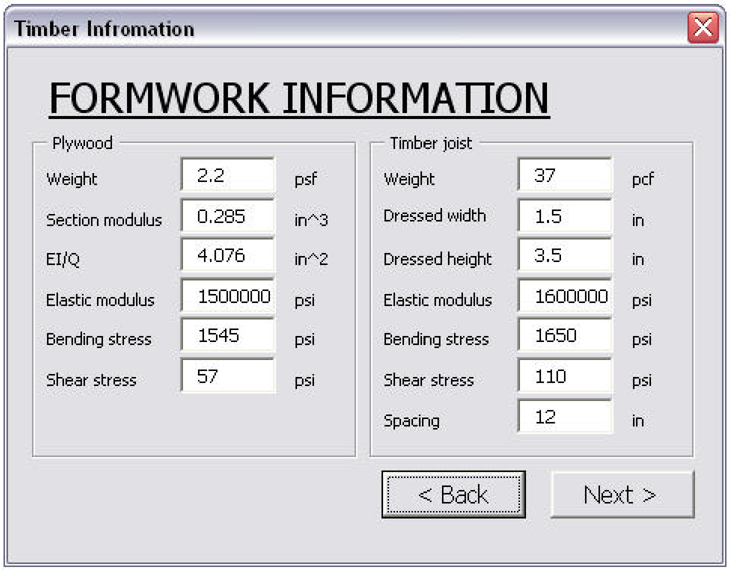
Bracket information

Bracket safe load and dimensions are provided by the manufacturer. The inputs are base on the angle of the bracket leg or the dimension of the bracket leg



Hanger information

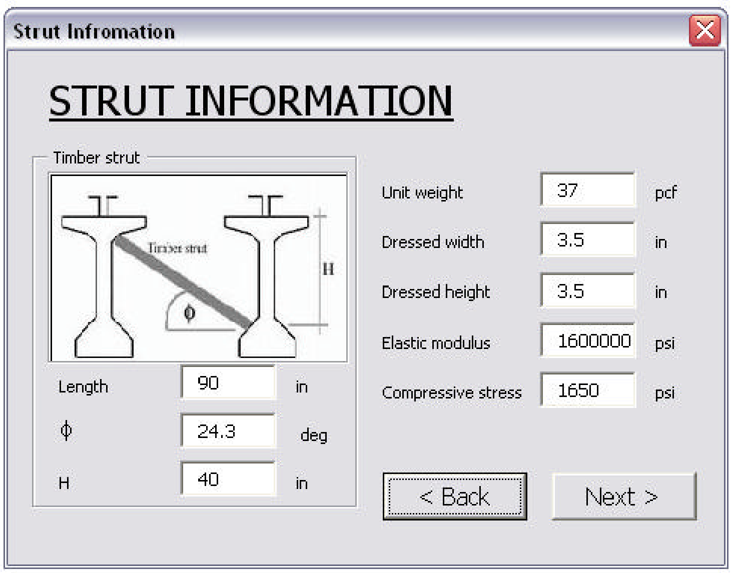
Input the position of the hanger and the hanger safe load. The position of the hanger is measured form the edge of the top flange of the girder.



Formwork information

Plywood that is usually used in the construction is ¾" thickness.

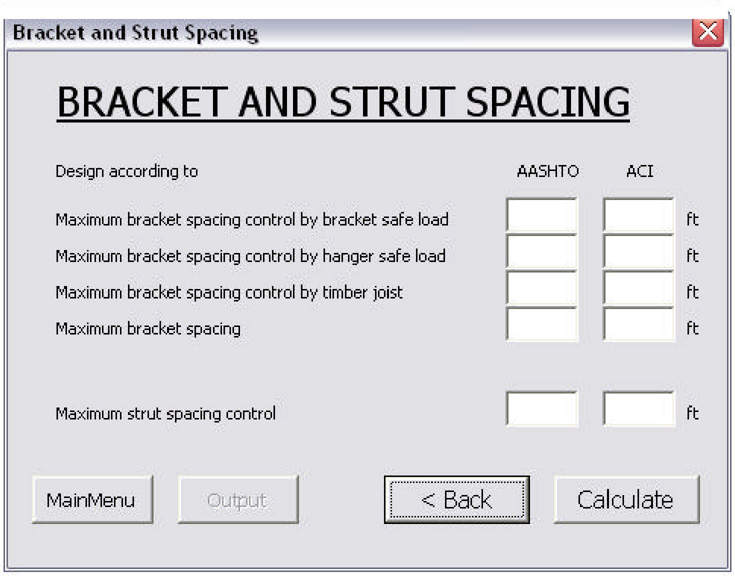
Input the allowable bending stress and shear stress, which depend upon the code.



Strut information

Input the allowable compressive stress and elastic modulus, which are taken from the code.

Length is measured in the inclined plane.



Result

Click "Calculate" to find the result.

Click "Output" to see all of the input and output.

3.3 Parameter range

The program has been tested and limits placed on the inputs to avoid calculation errors. The inputs are limited to avoid the error of calculation by a range of values, which depends on the possible value of each parameter. The ranges of parameters are listed in Table 1 below.

Table 1: Range of Parameters for Program Input

Girder				
Girder type				
Depth	0	to	1000	In
Top flange width	0	to	1000	Ft
Girder spacing	0	to	50	Ft
Girder area	0	to	3000	in^2
Girder perimeter	0	to	3000	In
Slab overhang	0	to	50	ft
Average slab thickness	0	to	100	in
28 days compressive strength	0	to	20000	ksi
Screed				
Screed max. wheel load	0	to	20000	lb
Minimum wheel spacing(W1)	0	to	30	ft
Maximum wheel spacing(W2)	0	to	30	ft
Bracket and Hanger				
Bracket top cord length	0	to	300	ft
Height of bracket	0	to	200	in
Bracket diagonal cord angle	0	to	90	in
Bracket vertical cord angle	0	to	180	deg
Bracket safe load	0	to	20000	lb
Hanger position from the edge of girder	0	to	100	in
Hanger safe load	0	to	20000	lb

Table 1: Range of Parameters for Program Input (continued)

Timber Falsework Data:				
Plywood				
Weight	0	to	300	pcf
Section modulus	0	to	100	in^3
Ib/Q	0	to	50	in^2
Elastic modulus	0	to	5000000	psi
Joists				
Joist spacing	0	to	15	in
Height (dressed size)	0	to	20	in
Width (dressed size)	0	to	20	in
Unit weight	0	to	100	pcf
Elastic modulus	0	to	5000000	psi
Allowable bending stress	0	to	3000	psi
Allowable shear stress	0	to	500	psi
Timber Strut				
Length of timber strut	0	to	400	in
Height (dressed size)	0	to	20	in
Width (dressed size)	0	to	20	in
Allowable compressive strength	0	to	3000	lb
Angle from the horizontal axis	0	to	90	deg
Position from the top of girder	0	to	400	in

3.4 Calculation

This program separates the calculation into three parts; formwork, falsework, and bracing. The first two calculations give the limitation for the maximum bracket spacing. The third gives the maximum strut spacing for resisting torsion on the concrete girder.

3.4.1 Formwork

Formwork consists of plywood form and joists supported by a bracket. The properties of plywood can be found in the product specification. The allowable bending strength and maximum deflection are according to the ACI or AASHTO specification. These criteria limit the spacing of the joist. Usually, if ¾” plywood is used in the construction, the maximum spacing of joist is less than 14”

The maximum span of the joist is the maximum spacing of the bracket. Therefore, maximum bending stress, shear stress, and deflection should be found and checked with the ACI or AASSTO specification in order to find the maximum bracket spacing. This bracket spacing is called “Maximum bracket spacing controlled by timber joist”.

3.4.2 Falsework

The more spacing a bracket has, the more load the bracket legs and the hanger carry. Assuming that the hanger does not fail, the spacing where one of the bracket legs reaches its safe load is called the "Maximum bracket spacing controlled by bracket safe load". Similarly for the hanger, assuming that the bracket legs do not fail, the spacing where the hanger reaches its safe load is called the "Maximum bracket spacing controlled by hanger safe load".

The bracket spacing is control by the maximum span of the joist, bracket safe load, and hanger safe load. The lowest of the three is the maximum bracket spacing.

3.4.3 Torsion

Constructing the overhang slab can result in excessive torsion on the girder which can cause the girder to crack. The bracing system should be spaced sufficiently close in order to prevent cracking. The maximum cracking torque can be calculated using equations found in the ACI and AASHTO codes. The value depends upon the cross section area and perimeter of the girder, as well as the percent of prestressing force. The bracing system consists of a timber strut which carries the compression force and a tied bar carrying the tension force. The maximum brace spacing depends on the capacity of the timber strut.

3.5 Results

The results of the program are separated into three parts as outlined above. The maximum bracket spacing is the lowest of the three results; either the hanger failure, bracket failure, or joist failure. The ACI and AASHTO codes follow the same approach as in the NDS specification, except for the specified allowable deflection criteria. The AASHTO code allows a structure to deflect more than the ACI code. Therefore, the AASHTO bracket spacing result is larger than that determined in the ACI code.

There are three outputs from this program; the summary output, and the detail outputs taken from the ACI code and the AASHTO code. The output sheets can be viewed and printed after the calculation is complete. A sample of the output for one example is included in Appendix A. The first page of the results is a summary of input and calculation results. The subsequent sheets provide complete calculation results for the AASHTO and ACI calculation procedures respectively.

4.0 Recommendations and Conclusions

4.1 Overview

The objective of this research study was to evaluate the current NCDOT procedures for design and analysis of bridge deck overhang falsework systems. The objective was accomplished by conducting an independent review of the guidelines and procedures utilized by the NCDOT for the design and analysis of falsework systems. The independent review was conducted by each of the principle investigators of this project. Discussions with outside consultants, contractors and NCDOT engineers were initiated to gain their perspective of the design process for falsework systems. The results of these discussions, our independent review and the review of other state DOT's provisions were utilized to develop the recommendations, observations and conclusions included in this report.

4.2 Observations, Recommendations and Conclusions

The primary observations, recommendations and conclusions developed as a part of this study are presented herein in bulleted format.

- The overhang falsework analysis and design procedures, as presented in this report and utilized by the NCDOT, are complete and in accordance with basic engineering principles and the current ACI and AASHTO specifications. The procedures closely follow the applicable specifications and do rely upon engineering judgment.

- The design consultants and contractors strongly prefer that a summary of the accepted falsework design and analysis requirements utilized by the NCDOT be made available for their use in preparing the falsework design submittal package. As an alternative, the utilization of standard NCDOT falsework details would eliminate any uncertainty in the preparation of the falsework submittal.

- The NCDOT overhang falsework analysis and design procedures appear to be consistent with other state DOT's requirements. However, some states only require that the calculations be performed in accordance with accepted engineering practice and that the calculations be performed and sealed by a Professional Engineer licensed within their state. In these cases, the implementation of the specification requirements is left to the judgment of the Professional Engineer without significant input from the DOT.

- The procedure for the analysis of the overhang bracket and determination of the maximum hanger load is consistent with accepted engineering principles. Discussions with the bracket manufacturers revealed that an alternative empirical method is available for the determination of the bracket loads. The empirical method is based upon testing conducted by the manufacturer. The use of this method in some cases may provide a more accurate analysis for the specific products utilized within the field.
- The utilization of stay-in-place (SIP) forms (steel deck) to provide lateral stability to the bridge girders during construction is not a common practice. Limited research has been conducted in this area by other state DOT's.
- The utilization of tie-bars connected between the tops of the outside girders to reduce the torsional stresses on the girders due to the overhang falsework loads follows accepted engineering principles. However, the contractors indicated that the required use of tie-bars was not common in other regions. In addition, the contractors mentioned that in their recent experience, the tie bars remained slack during the construction process indicating that significant load was not being transferred through the tie-bar system.
- The utilization of timber struts connected between the bottom flange of the outside girder and the top flange of the adjacent girder to reduce the torsional stresses on the girders due to the overhang falsework loads follows accepted engineering principles. However, the contractors indicated that the installation of these members is very time consuming and

labor intensive. It was suggested for prestressed girders, that the use of steel diaphragms (permanent or temporary) could be a reasonable alternative. The spacing of the steel diaphragms is dependent upon the torsional strength of the girder and the allowable strength of the diaphragm. Since the steel diaphragm could be fabricated with a top and bottom struts, it would be possible to reduce or eliminate the need for the tie-bars installed across the top of the girders.

- The *Falsework Evaluation* spreadsheet program developed as a result of this research was prepared in accordance with current NCDOT practice. Particular care was taken to verify that each of the calculations was in accordance with the ACI and AASHTO design specifications. In addition, the specifications were utilized to ensure that all of the necessary provisions were included in the NCDOT procedures. The spreadsheet program can be utilized to verify the results of a falsework submittal, to assist in the development of standardized details and to investigate the required spacing of alternate falsework components such as higher capacity brackets, hangers, or temporary steel diaphragms.

4.3 Implementation and Technology Transfer Plan

The final results and recommendations provided by this research can be implemented immediately by the NCDOT personnel to update the current falsework design and analysis procedures and develop standardized falsework details. The dissemination of the project findings is an integral part of this project. The Research Team will work with the NCDOT personnel on developing the most effective means to transfer the knowledge gained in this project to appropriate personnel at the various divisions and districts within the NCDOT.

4.4 Recommended Future Research

It is recommended that the utilization of tie-bars connected across the top of the two outside girders to reduce the torsional stress in the girders be further investigated to determine their effectiveness. Of particular interest is the load distribution and relative stiffness of the components within the falsework system. The investigation should include analytical stiffness modeling and field measurement during construction.

5.0 References

AASHTO (2002). *Standard Specifications for Highway Bridges, Seventeenth Edition*, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (1995a). *Guide Design Specifications for Bridge Temporary Works,* American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (1995b). *Construction Handbook for Bridge Temporary Works*, American Association of State Highway and Transportation Officials, Washington, D.C.

ACI (2001). *347R-01: Guide to Formwork for Concrete,* American Concrete Institute, Farmington Hills, MI.

ACI (1991). 3*45R-91: Guide for Concrete Highway Bridge Deck Construction*, American Concrete Institute, Farmington Hills, MI.

Hurd, M.K. (1995). *ACI SP-4, Formwork for Concrete, 6th Edition,* American Concrete Institute, Farmington Hills, MI.

Appendix A – Sample Output from the *Falsework Evaluation* Spreadsheet Program

Overhang Bracket Spacing

Back to the program

Input

Girder

Girder type	AASHTO TYPE IV	
Depth	54	in
Top flange width	1.6666667	ft
Girder spacing	7.833	ft
Girder area	789	in^2
Girder perimeter	166.42	in
Slab overhang	2.5	ft
Average slab thickness	12	in
Concrete weight	150	pcf
28 days compressive strength	5000	ksi

Screed

Screed max. wheel load	1000	lb
Minimum wheel spacing(W1)	1.75	ft
Maximum wheel spacing(W2)	5.333	ft

Bracket and Hanger

Bracket top cord length	4.5	ft
Height of bracket	53.84	in
Bracket diagonal cord angle	41.9	in
Bracket vertical cord angle	83.64	deg
Bracket safe load	3600	lb
Hanger safe load	6000	lb

Timber Falsework Data:

Plywood		
Weight	2.2	pcf
Section modulus	0.285	in^3
Ib/Q	4.076	in^2
Elastic modulus	1500000	psi
Joists		
Joist spacing	12	in
Height (dressed size)	3.5	in
Width (dressed size)	1.5	in
Weight	37	pcf
Timber Strut		
Maximum spacing	14.58	ft
Length of timber strut	98	in
Height (dressed size)	3.5	in
Width (dressed size)	3.5	in
Section modulus	1600000	psi
Allowable compressive strength	1650	lb
Angle from the horizontal axis	24.3	deg
Position from the top of girder	40	in

Output

	AASHTO	ACI
Max. joist spacing controlled by plywood (ft)	11.69	11.69
Max. bracket spacing when hanger fails (ft)	4.68	4.68
Max. bracket spacing when diagonal bracket fails (ft)	9.27	9.27
Max. bracket spacing controlled by joist (ft)	4.55	3.45
Max. bracket spacing (ft)	4.55	3.45
Max. bracing spacing when girder crack (ft)	112.49	112.49
Max. bracing spacing when timber strut fail (ft)	12.61	12.61
Max. bracing spacing (ft)	12.61	12.61

Calculations in accordance with the ACI specification

Input information

Girder		
Girder type	AASHTO TYPE IV	
Depth	54	in
Top flange width	1.66667	ft
Girder spacing	7.833	ft
Girder area	789	in^2
Girder perimeter	166.42	in
Slab overhang	2.5	ft
Average slab thickness	12	in
Concrete weight	150	pcf
28 days compressive strength	5000	ksi
Screed		
Screed max. wheel load	1000	lb
Minimum wheel spacing(W1)	1.75	ft
Maximum wheel spacing(W2)	5.333	ft
Bracket and Hanger		
Bracket top cord length	4.5	ft
Height of bracket	53.84	in
Bracket diagonal cord angle	41.9	in
Bracket vertical cord angle	83.64	deg
Bracket safe load	3600	lb
Hanger position from the edge of girder	6	in
Hanger safe load	6000	lb
Timber Falsework Data:		
Plywood		
Weight	2.2	pcf
Section modulus	0.285	in^3
Ib/Q	4.076	in^2
Elastic modulus	1500000	psi
Joists		
Joist spacing	12	in
Height (dressed size)	3.5	in
Width (dressed size)	1.5	in
Unit weight	37	pcf
Elastic modulus	1600000	psi
Allowable bending stress	1650	psi
Allowable shear stress	110	psi
Timber Strut		
Maximum spacing	14.58	ft
Length of timber strut	98	in
Height (dressed size)	3.5	in
Width (dressed size)	3.5	in
Section modulus	1600000	psi
Allowable compressive strength	1650	lb
Angle from the horizontal axis	24.3	deg
Position from the top of girder	40	in
Strut spacing	12.6093	ft

Analysis of formwork

Check bending stress in plywood

Loads

Slab dead load	=	Overhang length x Slab thickness x concrete unit weight				
	=	152.2	psf			
Plywood	=	2.2	psf			
Const. LL	=	50	psf			
Total , w	=	202.2	psf			

Maximum moment , M = $\frac{w * L^2}{8}$

= 25.28 lb-ft

Bending stress = moment / section modulus

= 1064 psi < 1545 psi OK

(Allowable bending stress)

Check deflection in plywood

deflection = $\frac{5 * w * L^4}{384 * E * I}$

= 0.036 in

Allowable deflection = L / 360 or 1/16" OK

Check rolling shear in plywood

Shear force, V = $\frac{w * L}{2}$

= 202.2 lbs

Shear stress = $\frac{V * Q}{I * b}$

= 49.61 psi

< 57 psi

Check bending stress in timber joist

Total load , w = total load from plywood + joist dead load

= 203.5 lb/ft

Sect. modulus , S = 3.063 in^3

Allowable bending stress = 1650 psi

Moment , M = $\frac{w * L^2}{8}$

= 6311 lb-in

Bending stress = M / S

= 2061 psi

Check deflection in joist

deflection = $\frac{5 * w * L^4}{384 * E * I}$

= 0.172 in

Allowable deflection = L / 360 or 1/16"

Check rolling shear in joist

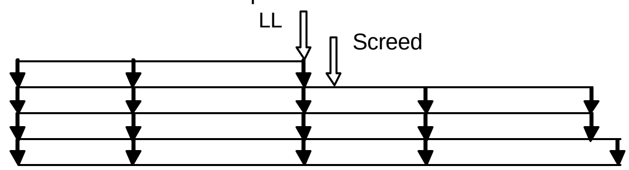
Shear force, V = $\frac{w * L}{2}$

= 462.7 lbs

Shear stress = $\frac{V * Q}{I * b}$

= 132.2 psi

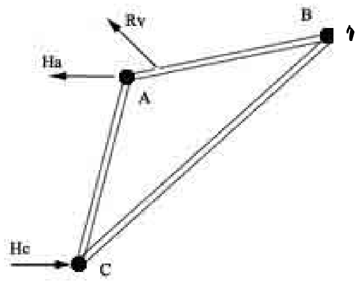
< 110 psi



Loads on Bracket

Concrete load	=	701.6	lb/ft	Length of load	=	2.5 ft
Form load	=	18.71	lb/ft	Length of load	=	4 ft
Uniform Live load	=	20	psf	Length of load	=	4 ft
Bracket load	=	14	lb/ft	Length of load	=	4.5 ft
Screed load	=	1000	lb	location of load	=	2.68 ft from support
Point live load	=	75	lb	location of load	=	2.5 ft from support

Bracket spacing =



On each bracket

Total vertical load =

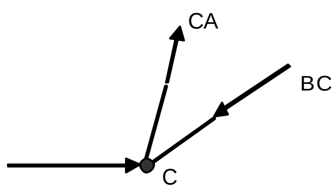
Σ Fy = 0

Rv = 4243 lb

Σ Md = 0

Hc = 1413 lb

Load on each bracket leg



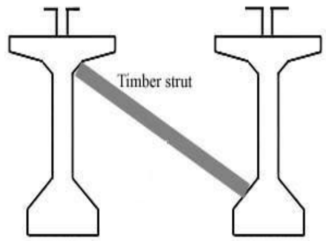
Σ Fy = 0

BC	=	2110	lb	<	3600	lb	(Bracket safe load)

Σ Md = 0

CA	=	1418	lb	<	3600	lb	(Bracket safe load)

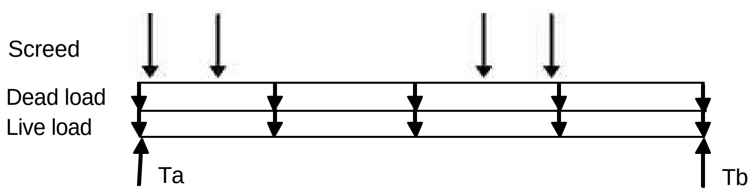
Timber struts and Rebar ties



Effective torsion on the girder

Case 1: Dead load only

Bracket load component	Load (lb/ft)	e (ft)	=	M (lb-ft/ft)
Slab	375	2.1		781
Form	16	2.8		45.3
Bracket	13.5	3.1		41.5
Net torsion	=			868



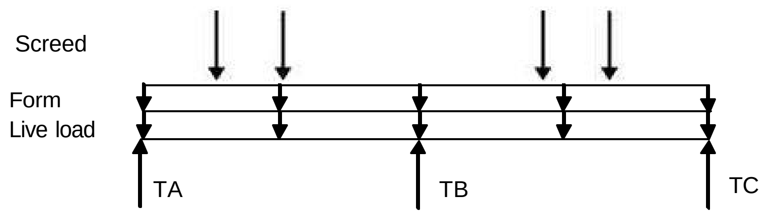
Case 2: Dead load plus live load

Uniform load component	Load	e	=	M
Const. LL	80	2.8		227
Line load	75	3.3		250
Screed	1000	3.5		3510

Σ Ma = 0

Tb	=	15364	lb-ft/ft	
	<	78980	lb-ft/ft	(Cracking Torque) OK

Effective Torsion on bracing



Case1: Dead load only
From previous "Case 1"

T_{DL}	=	1736	lb-ft/ft
Force in timber strut	=	T_{DL} / A_m	
	=	497	lb

Find timber strut capacity

Timber strut acts like "pinned-end" column

K_e	=	1	
l_e	=	98	in
fc	<=	$Fc * C_D * C_m * C_t * C_F * C_i * C_P$	
	=	Fc'	
Fc	=	1650	psi
C_D	=	1.6	
C_m	=	1	
C_t	=	1	
C_F	=	1	
C_i	=	1	
Fc*	=	$Fc * C_D * C_m * C_t * C_F * C_i$	
l_e / d	=	28	
E'	=	$E * C_m * C_t * C_i$	
	=	2E+06	psi
K_{CE}	=	0.3	
c	=	0.8	
F_{CE}	=	$\frac{KCE * E'}{(le / d)^2}$	
	=	612.2	psi
C_P	=	$\frac{1 + (F_{CE} / F_C^*)}{2 * c} - \sqrt{\left[\frac{1 + (F_{CE} / F_C^*)}{2 * c}\right]^2 - \frac{F_{CE} / F_C^*}{c}}$	
	=	0.22	
Fc'	=	$Fc * C_D * C_m * C_t * C_F * C_i * C_P$	
	=	579.6	psi
fc	=	40.57	psi
	<=	Fc'	OK

Case 2: Dead load and live load

Σ $M_A = 0$			
T_B	=	24807	lb-ft/ft
P_T	=	T_B / A_M	
	=	6471	lb
Pc	=	$P_T / \cos\theta$	
	=	7100	lb
fc	=	Pc / Area	
	=	579.6	psi
	<	Fc'	OK

Calculations in accordance with the AASHTO specification

Input information

Girder		
Girder type	AASHTO TYPE IV	
Depth	54	in
Top flange width	1.66667	ft
Girder spacing	7.833	ft
Girder area	789	in^2
Girder perimeter	166.42	in
Slab overhang	2.5	ft
Average slab thickness	12	in
Concrete weight	150	pcf
28 days compressive strength	5000	ksi
Screed		
Screed max. wheel load	1000	lb
Minimum wheel spacing(W1)	1.75	ft
Maximum wheel spacing(W2)	5.333	ft
Bracket and Hanger		
Bracket top cord length	4.5	ft
Height of bracket	53.84	in
Bracket diagonal cord angle	41.9	in
Bracket vertical cord angle	83.64	deg
Bracket safe load	3600	lb
Hanger position from the edge of girder	6	in
Hanger safe load	6000	lb
Timber Falsework Data:		
Plywood		
Weight	2.2	pcf
Section modulus	0.285	in^3
Ib/Q	4.076	in^2
Elastic modulus	1500000	psi
Joists		
Joist spacing	12	in
Height (dressed size)	3.5	in
Width (dressed size)	1.5	in
Unit weight	37	pcf
Elastic modulus	1600000	psi
Allowable bending stress	1650	psi
Allowable shear stress	110	psi
Timber Strut		
Maximum spacing	14.58	ft
Length of timber strut	98	in
Height (dressed size)	3.5	in
Width (dressed size)	3.5	in
Section modulus	1600000	psi
Allowable compressive strength	1650	lb
Angle from the horizontal axis	24.3	deg
Position from the top of girder	40	in
Strut spacing	12.6093	ft

Analysis of formwork

Check bending stress in plywood

Loads

Slab dead load	=	Overhang length x Slab thickness x concrete unit weight				
	=	152.2	psf			
Plywood	=	2.2	psf			
Const. LL	=	50	psf			
Total , w	=	202.2	psf			
Maximum moment , M	=	$\frac{w * L^2}{8}$				
	=	25.28	lb-ft			
Bending stress	=	moment / section modulus				
	=	1064	psi <	1545	psi	OK
				(Allowable bending stress)		

Check deflection in plywood

deflection	=	$\frac{5 * w * L^4}{384 * E * I}$			
	=	0.036	in		
Allowable deflection	=	L / 360	or	1/16"	OK

Check rolling shear in plywood

Shear force, V	=	$\frac{w * L}{2}$	
	=	202.2	lbs
Shear stress	=	$\frac{V * Q}{I * b}$	
	=	49.57	psi
	<	57	psi

Check bending stress in timber joist

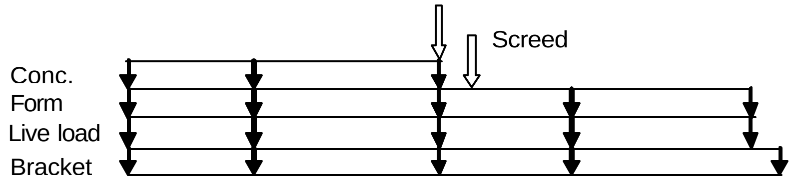
Total load , w	=	total load from plywood + joist dead load	
	=	203.5	lb/ft
Sect. modulus , S	=	3.063	in^3
Allowable bending stress	=	1650	psi
Moment , M	=	$\frac{w * L^2}{8}$	
	=	6311	lb-in
Bending stress	=	M / S	
	=	2061	psi

Check deflection in joist

deflection	=	$\frac{5 * w * L^4}{384 * E * I}$		
	=	0.172	in	
Allowable deflection	=	L / 360	or	1/16"

Check rolling shear in joist

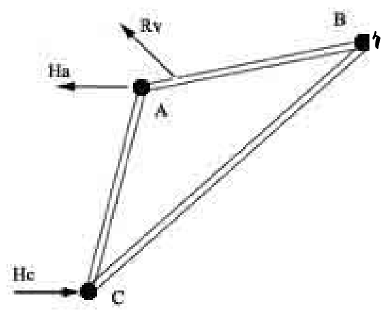
Shear force, V	=	$\frac{w * L}{2}$	
	=	462.7	lbs
Shear stress	=	$\frac{V * Q}{I * b}$	
	=	132.2	psi
	<	110	psi



Loads on Bracket

Concrete load	=	935.6	lb/ft	Length of load	=	2 ft
Form load	=	24.95	lb/ft	Length of load	=	4 ft
Uniform Live load	=	20	psf	Length of load	=	4 ft
Bracket load	=	14	lb/ft	Length of load	=	4.5 ft
Screed load	=	666	lb	location of load	=	2.18 ft from support
Point live load	=	75	lb	location of load	=	2 ft from support

Bracket spacing =



On each bracket

Total vertical load =

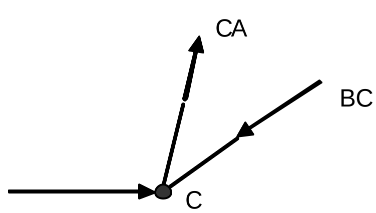
Σ Fy = 0

Rv	=	4243	lb

Σ Md = 0

Hc	=	1051	lb

Load on each bracket leg



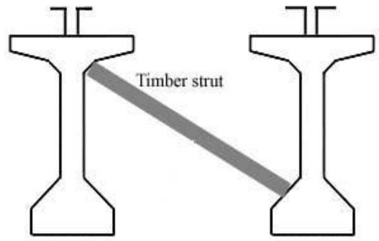
Σ Fy = 0

BC	=	1570	lb	<	3600 lb	(Bracket safe load)

Σ Md = 0

CA	=	1059	lb	<	3600 lb	(Bracket safe load)

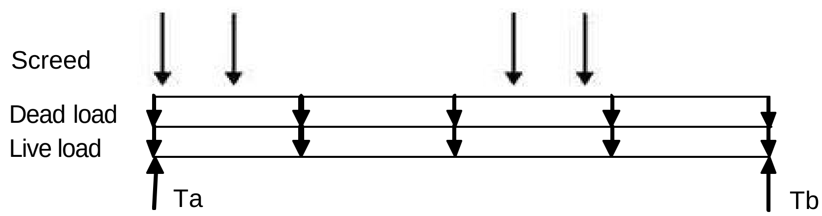
Timber struts and Rebar ties



<u>Effective torsion on the girder</u>

Case 1: Dead load only

Bracket load component	Load (lb/ft)	e (ft)	=	M (lb-ft/ft)
Slab	300	2.8		825
Form	16	3.8		60
Bracket	10.1	4		40.4
Net torsion	=			925



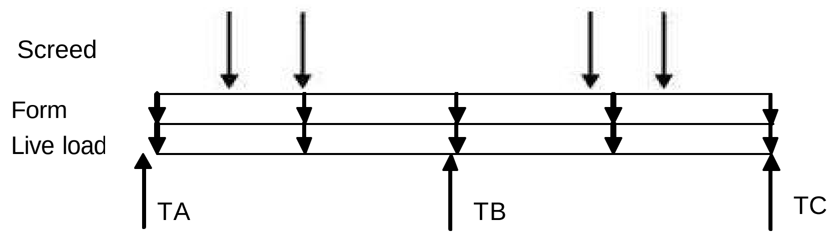
Case 2: Dead load plus live load

Uniform load component	Load	e	=	M
Const. LL	80	3.8		300
Line load	75	3.8		281
Screed	666	3.9		2615

Σ Ma = 0

Tb	=	17498	lb-ft/ft
	<	94911	lb-ft/ft (Cracking Torque) OK

Effective Torsion on bracing



Case1: Dead load only
From previous "Case 1"

T_{DL}	=	1851	lb-ft/ft
Force in timber strut	=	T_{DL} / A_m	
	=	529.8	lb

Find timber strut capacity

Timber strut acts like "pinned-end" column

K_e	=	1	
l_e	=	90	in
fc	<=	$F_c * C_D * C_m * C_t * C_F * C_i * C_P$	
	=	Fc'	
Fc	=	1650	psi
C_D	=	1.6	
C_m	=	1	
C_t	=	1	
C_F	=	1	
C_i	=	1	
Fc*	=	$F_c * C_D * C_m * C_t * C_F * C_i$	
l_e / d	=	25.71	
E'	=	$E * C_m * C_t * C_i$	
	=	2E+06	psi
K_{CE}	=	0.3	
c	=	0.8	
F_{CE}	=	$\frac{KCE * E'}{(le / d)^2}$	
	=	725.9	psi
C_P	=	$\frac{1 + (F_{CE} / F_C^*)}{2 * c} - \sqrt{\left[\frac{1 + (F_{CE} / F_C^*)}{2 * c}\right]^2 - \frac{F_{CE} / F_C^*}{c}}$	
	=	0.257	
Fc'	=	$F_c * C_D * C_m * C_t * C_F * C_i * C_P$	
	=	678.9	psi
fc	=	43.25	psi
	<=	Fc'	OK

Case 2: Dead load and live load

Σ $M_A = 0$

T_B	=	29056	lb-ft/ft
P_T	=	T_B / A_M	
	=	7580	lb
Pc	=	$P_T / \cos\theta$	
	=	8317	lb
fc	=	Pc / Area	
	=	678.9	psi
	<	Fc'	OK