FHWA: DEEP BEAM DESIGN

By: Alejandra Quesada

FINAL DESIGN REPORT

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Acknowledgements

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1.0 Project Description

The intent of this project is to improve on the design of deep beams and research alternative ways to provide steel reinforcement in order to reduce crack sizes in concrete. The project includes the following processes: design, construction, testing, analysis, and reporting. The objective of the project is to quantify the amount of steel fibers necessary to supplement the conventional reinforcement required for deep beams. In other words, it is meant to evaluate the relationship between fiber/rebar content and crack widths under load.

This project also meets the fellowship requirements established by FHWA within their student application packet. The FHWA fellowship requires that the project be related to the field of transportation and make a difference in the transportation industry. The requirements set forth by FHWA are:

- Undergraduate and graduate recipients shall prepare a thesis/dissertation, or research paper on a topic directly related to a relevant transportation problem or issue. The Faculty Advisor should approve topics.
- Recipients are required to attend the Transportation Research Board (TRB) Conference held in January 2014 in Washington, D.C. and be prepared to present their project.
- Students must submit an abstract for possible selection to present at a poster session during the TRB Conference.
- If selected, a poster is required, along with a 5 min summary presentation of the project.
- Submittal of a final report summarizing all research data and analysis.

The purpose of the Dwight D. Eisenhower Transportation Fellowship Program is to stimulate interest among Minority Institutions of Higher Education (MIHE) students in conducting transportation-related research, pursue transportation-related degrees, to enter the transportation workforce. The proposal of the project was to provide a summary of how the plan of study will impact and enhance the field of transportation [3].

Previously, researchers have studied fiber reinforced deep beams; however, they have not specifically examined the correlation between the fiber percentage and the minimum amount of web reinforcement [1]. "Past studies (Narayanan and Darwish 1988; Mansur and Ong 1991) have shown that including discrete fibers enhances the strength and deformation capacities of deep beams and provides better crack control" [2]. As such, there is a demand for deep beam research where the primary variable is the quantity of fibers provided in the concrete mixture.

2.0 Background

This project focuses on the design and improvement of deep beams. A deep beam is a beam with a short shear span, as seen in the red box in Figure 2.1 below.

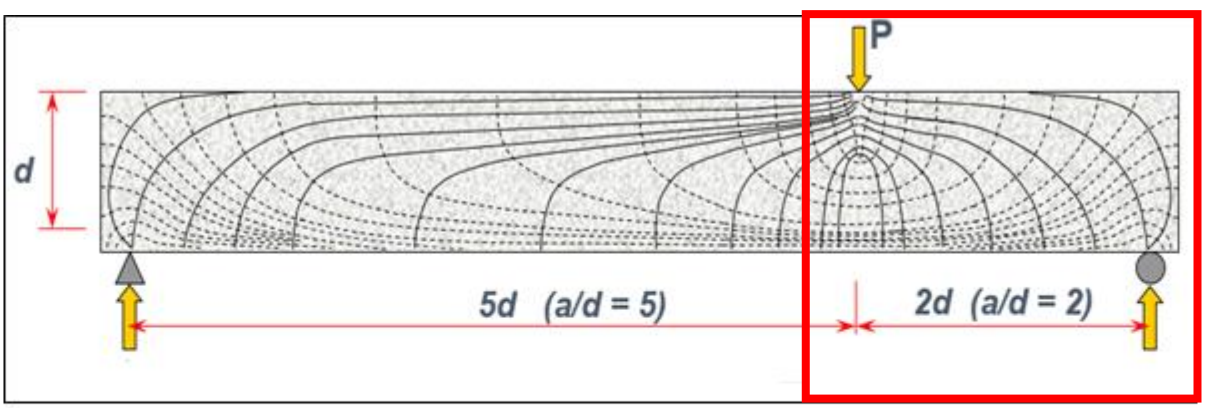

Figure 2.1: Deep Beam Definition

This means that a deep beam has a low span (a)-to-depth (d) ratio of $a/d \leq 2$. Only the right side of Figure 2.1 would be considered a deep beam due to how the beam would crack after being loaded by a load, P. The cracks are more bottle-shaped because the distance between the load and support are very close together. This distance is the span (a) of the beam that is compared to its depth (d) to identify it as a deep beam.

Deep beams are used in almost all bridges. They are used widely in bridge supports to hold the span of a bridge over a column, as seen in Figure 2.2 below.

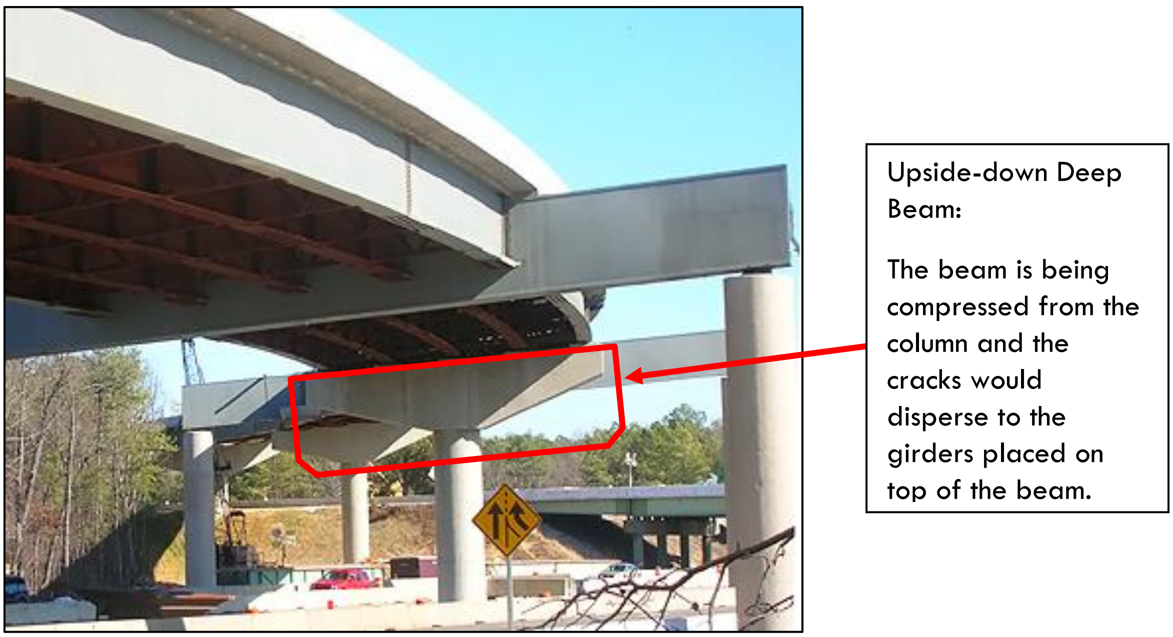

Figure 2.3: Deep Beam Example

According to the American Association of State Highway and Transportation Officials (AASHTO), deep beams must contain a minimum amount of reinforcement equivalent to 0.3% of the cross-sectional area in both the vertical and horizontal directions. Researchers have shown that this quantity is not a strength requirement. Rather, it is required to control cracking or, limit the maximum crack width to less than 0.016 inches under the application of service loads. Steel fiber reinforcement is known to be highly effective at limiting crack widths in concrete [3]. The steel fibers used in this project can be seen in Figure 2.4. These fibers were 1.5 in. long and added directly to the concrete mix.

Figure 2.4: Steel Fibers - with flat heads

When considering the actual size of these members, the quantity of reinforcement necessary to meet the AASHTO minimum requirement is substantial and installation is labor intensive. It is likely that the steel congestion and subsequent labor costs to construct these members can be reduced through the addition of steel fibers. This would likely decrease the maximum crack widths of these structures; thereby increasing their serviceability performance. For this project, "serviceability performance" is quantified as the rate of growth of the width of the maximum diagonal crack.

3.0 Identification of Alternative Beam Designs

Using deep beam proportion guidelines from Appendix A and section 11.7 of Concrete Code ACI-318, a width, depth, and length were selected for a basic deep beam design. Also based on this code, the amount of minimum reinforcement was calculated for each beam design and the sizes of the rebar diameters were chosen. 3 different deep beam designs were developed in order to ensure that there were enough specimens for 9 different variables. 3 beams of each design (9 beams total) was enough to have one beam of each variable design (discussed further in section 4.0 of this report). These were chosen to be approximately 12 inches wide, 18 inches deep, and 6 feet long. These dimensions were selected using a depth to span ratio of less than 2, and using tables from the concrete ACI-318: Appendix A code book. With a minimum area of reinforcement required by the code, a bar diameter was selected and the amount of bars could be determined. There were 4 #5 bars for compression steel at the top, and 4 #8 bars for tension steel at the bottom. The number of the bar refers to the diameter of the bar. For example, a #5 bar means it's 5/8 in. in diameter and a #3 means it's 3/8 in. in diameter. The three designs selected involve a minimally reinforced beam and two beams with slightly more reinforcement. The purpose of this extra rebar in the second and third designs is to provide more tensile strength in the test regions of the beam, shown in Figure 2. A detailed image of the 3 different beam designs can be seen in Figure 3.1. This figure shows the 3 final designs that were selected for this project and their test regions. The test regions are the areas of the beam that were analyzed for crack widths. The first design includes 0.0% additional reinforcement in the test region (labeled in the figure). The cross sectional view shows details of the dimensions of the beams. These dimensions are the same for all 9 beams. The second design shows slightly more rebar, about 0.2% more, in the test region of the beam. The diameter of the additional rebar for design 2 is 3/8 in. The final design shows 0.3% more conventional reinforcement in the test region. The diameters of these bars are ½ in; slightly larger than the bars used in design 2.

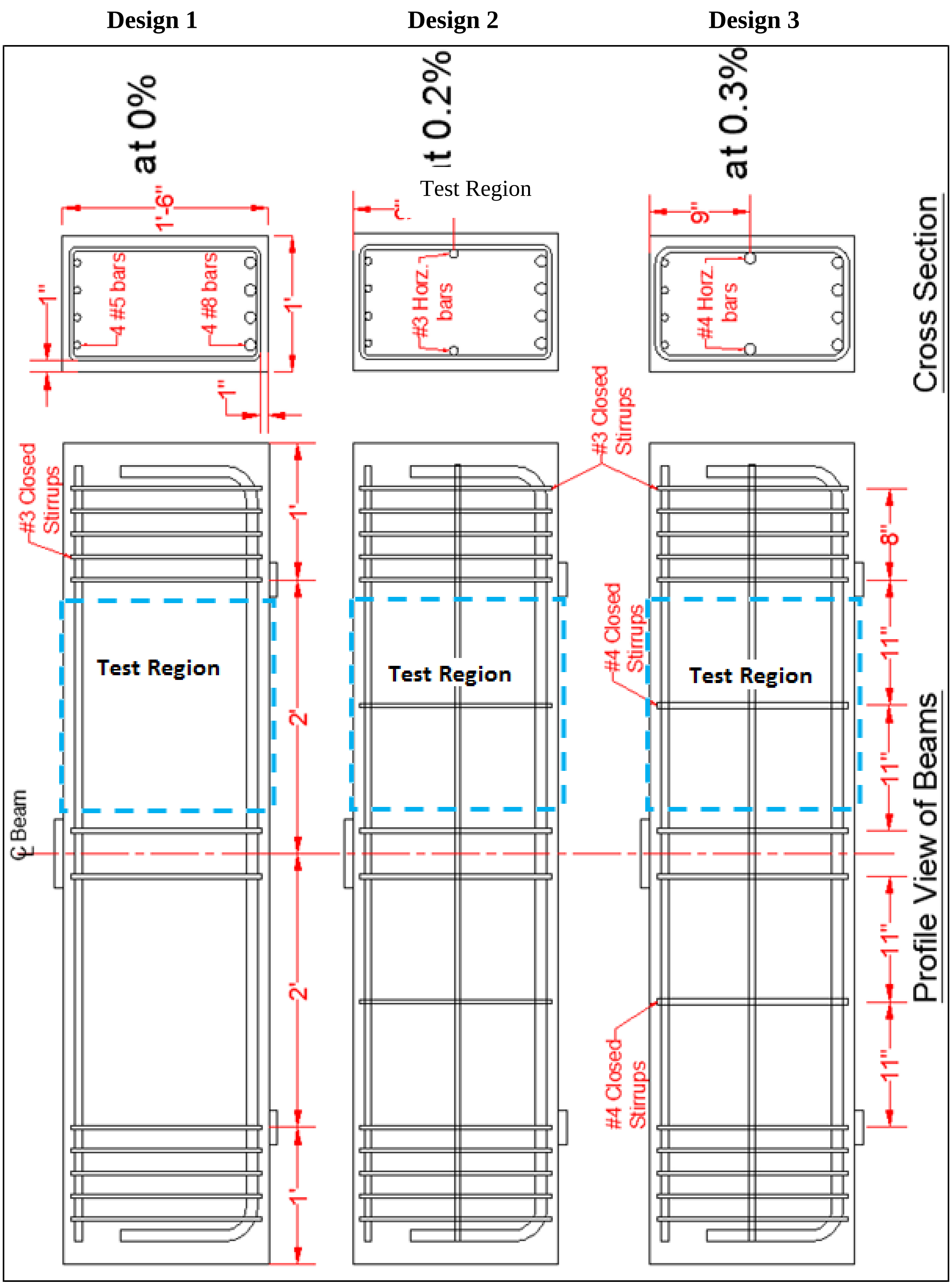

Figure 3.1: Design Alternatives

4.0 Beam Failure Analysis & Testing

Before testing, a beam failure analysis was performed to determine the minimum amount of shear strength of the weakest beam. In this case, the beam with no additional conventional reinforcement in the test region was analyzed for shear.

To begin gathering the values needed to do the shear analysis, a flexural analysis of the beam is performed. This analysis determines the strength of a beam, before a bending or flexural failure, given the dimensions. Figure 4.1, below, is an image of what the analysis looked like after it was completed. The left side of the image is a cross sectional view of the beam and the right side shows the stress graph of the beam. The compression caused in the beam (Cc and Cs) has to be equal to the tension in the beam (T) to form equilibrium. Setting these values equal to each other results in the following formula:

$$0.85 * f'c * b * \beta * c = \varepsilon_s * E_s * A_s' = f_y * A_s$$

where $f'c$ = specified compressive strength of concrete (psi)
b = width of compression face of member (in.)
β = ratio of long to short dimensions; clear spans for two-way slabs
c = distance from extreme compression fiber to neutral axis (in.)
E_s = modulus of elasticity of reinforcement and structural steel (psi)
A_s' = area of compression reinforcement (in^2)
A_s = area of nonprestressed longitudinal tension reinforcement (in^2)
f_y = specified yield strength of reinforcement (psi)

(Note: These definitions were taken from ACI-318 Concrete Code: Ch. 2-Notations and Definitions) [4]

Solving this formula for the variable, c, gives c = 3.52 in. The value, a, a parameter used to describe the depth of the rectangular stress block (as depicted in Figure 4.1) is equal to $c*\beta$, resulting in a= 2.98 in.

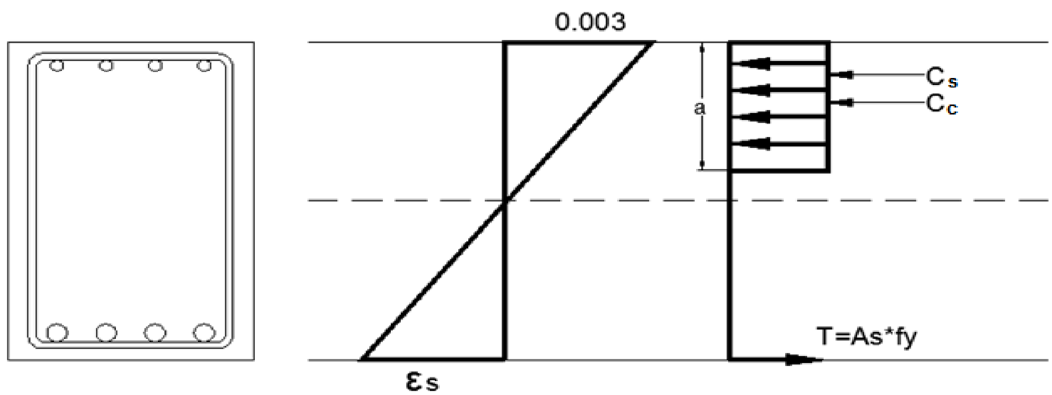

Figure 4.1: Beam Failure Analysis

Once the value of *a* was determined, it was used to find the values of ω_{s1} and ω_{s2}, which represent the longer sides of the nodes depicted in Figures 4.2 and 4.3. These values were used in a series of equations to find the shear strength values at all the different faces of the compression-compression-compression (CCC) node and the compression-compression-tension (CCT) node (depicted in Figures 4.2 and 4.3).

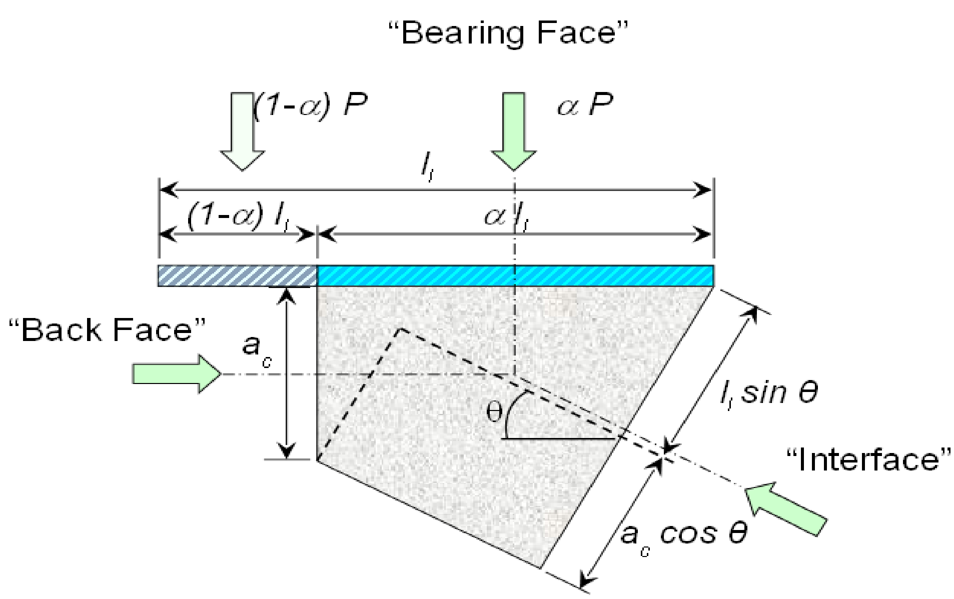

Figure 4.2: CCC Nodal View

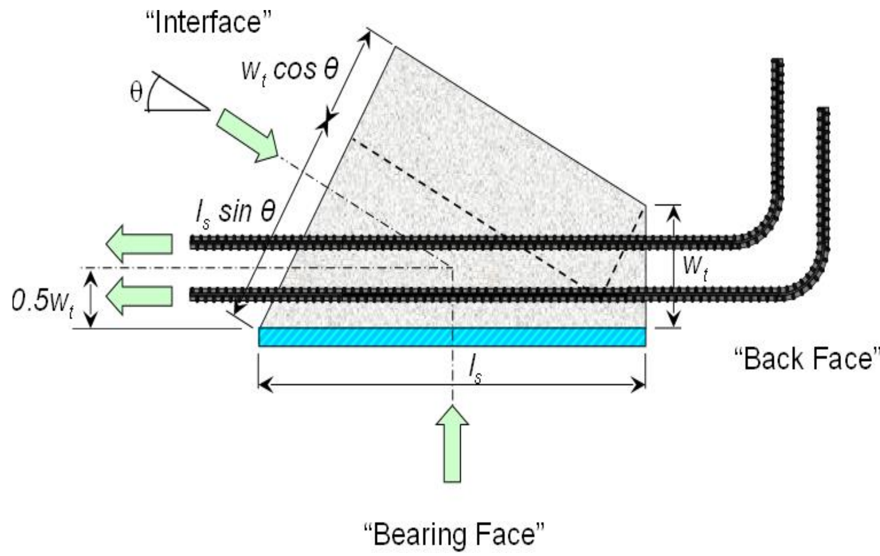

Figure 4.3: CCT Nodal View

These nodes are close up views of the nodal zones of a deep beam, shown in Figure 4.4. Figure 4.4 depicts half a beam and shows how the nodes are "connected" by a region of bottle-shaped cracks. These cracks model realistic shapes of deep beam failures. The area between the CCC and CCT nodes, a, is known as the "test region" of the deep beam.

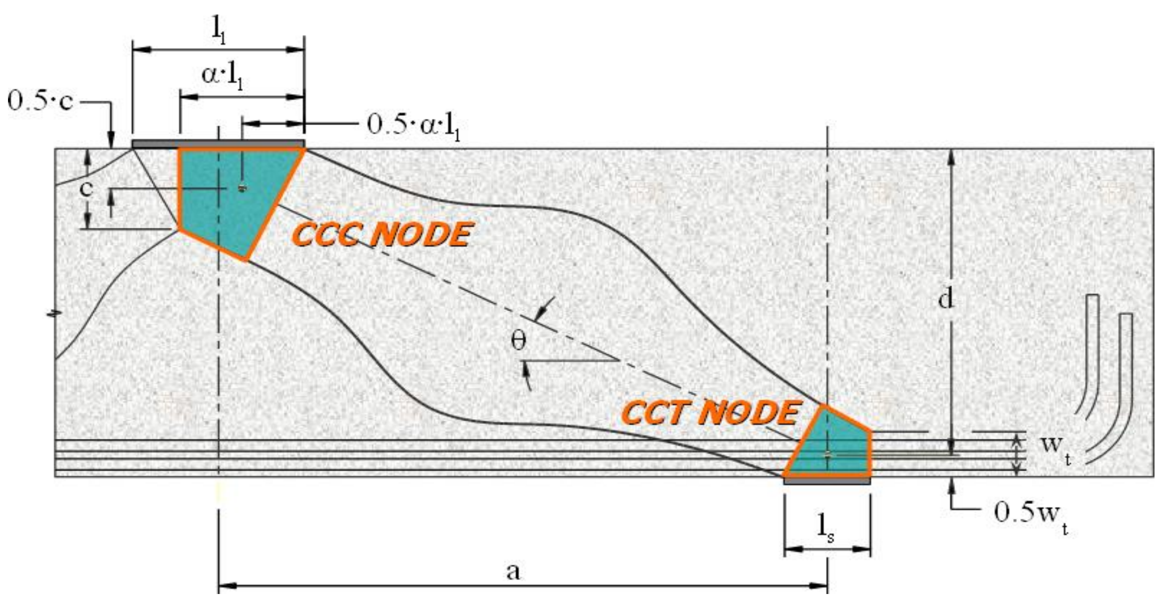

Figure 4.4: Deep Beam Nodal Zones

The following table shows the results of the calculations performed to determine the minimum shear value of any one of the nine beams:

Shear Strength Equations	Resulting Shear Value, Vn
$Vn = f_{ce}*A_{nz}$=0.85(1.0)(4.38ksi)(3")(12")	133.93 kips
$Vn/\tan\Theta = f_{ce}*A_{nz}$=0.85(1.0)(4.38ksi)(2.98")(12")	189.29 kips
$Vn/\sin\Theta = f_{ce}*A_{nz}$=0.85(0.75)(4.38ksi)(12")(5.02)	168.20 kips
$Vn/\sin\Theta = f_{ce}*A_{nz}$=0.85(0.6)(4.38ksi)(5.02)(12")	134.56 kips
$Vn = f_{ce}*A_{nz}$=0.85(0.8)(4.38ksi)(3")(12")	**106.97 kips**
$Vn/\tan\Theta$ = fy*As = (60ksi)(3.16 in^2)	189.6 kips
$Vn/\sin\Theta = f_{ce}*A_{nz}$=0.85(0.6)(4.38ksi)(4.78)(12")	127.98 kips

Table 4.5: Shear Value Results

As seen in Table 4.5 above, the lowest shear strength value determined was 106.97 kips. This means that the weakest beam will have a minimum shear of around 107 kips, but it will not necessarily fail at this load. This does not mean that the beam will fail at this shear; only that all the other beams will be stronger than the low value of 107 kips. This analysis was performed to predict the lowest shear strength out of all 9 beams. The actual locations of the cracks and the strengths at which they will occur cannot be determined through shear analysis, and will have to be determined after testing occurs.

As stated in the Design Alternatives section of this report, the experimental work included the testing of nine reduced-scale deep beam specimens. Specimens were approximately 12 inches wide and 18 inches deep and were tested with a span-to-depth ratio of approximately 1.8. Experimental variables include the volumetric percentage of steel fibers and the percentage of transverse web reinforcement, or rebar. Table 4.6, below, presents an overview of the testing program for this project:

SPECIMEN	TRANVERSE REINFORCEMENT RATIO	FIBER PERCENTAGE
1	0.3% each way	0%
2	0.2% each way	
3	0% each way	
4	0.3% each way	0.5%
5	0.2% each way	
6	0% each way	
7	0.3% each way	1.0%
8	0.2% each way	
9	0% each way	

Table 4.6: Testing Program Overview

The maximum diagonal crack width was measured for all specimens at multiple load increments up to approximately 75% of their ultimate capacity. The rate of growth of the crack widths for specimens with and without fibers were compared with one another and this relationship was used to quantify their serviceability performance.

Testing was completed using a number of different tools. The most important testing machine was an RC-series single purpose cylinder made by ENERPAC. The cylinder was used to compress the beams by being hydraulically loaded. An AutoCAD configuration of beam centered on the compressor can be seen in Figure 4.7. This image is drawn approximately to scale. A cross sectional view of the beam on the machine can be seen in Figure 4.8.

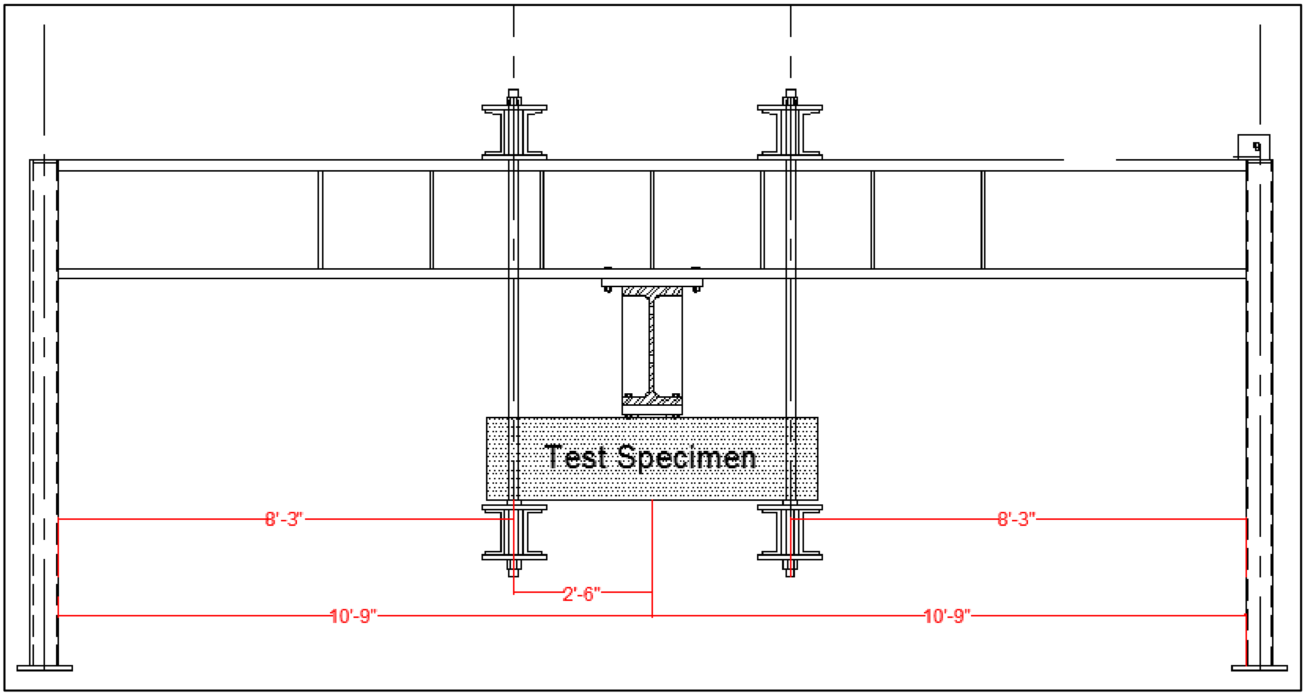

Figure 4.7: Hydraulic Compressor Configuration

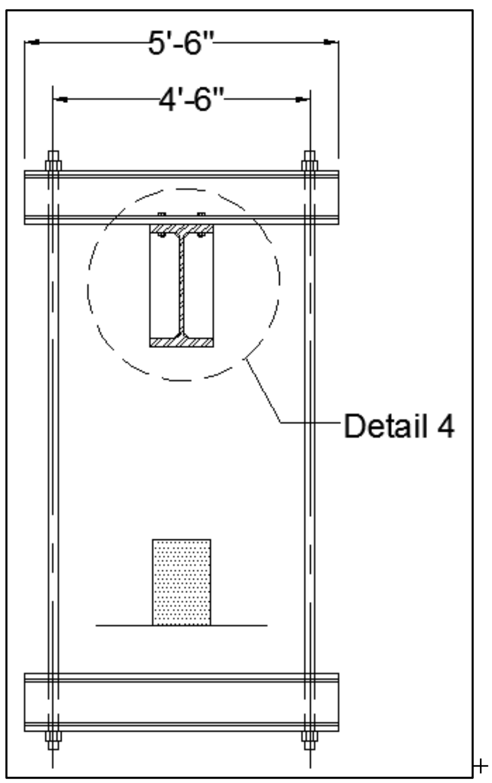

Figure 4.8: Cross-Sectional Compressor Configuration

The beams were moved into the testing lab by rolling them on steel pipes. Once in the lab room, they were lifted with a manual lift and centered on the supports of the compression machine. All 9 beams were successfully compressed to failure. Throughout the breaking process, the widths of any cracks created within the test region were measured using a crack width ruler (depicted in Figure 4.9) and recorded.

Figure 4.9: Crack Width Ruler

After all the data was collected, it was input into excel to create graphs and plots of strength versus crack width size. This data was then analyzed to determine if the addition of steel fibers within the concrete mix had any graphical and physical effect on crack control.

5.0 Conclusions & Recommendations

As previously stated, all data was collected and organized into excel spreadsheets according to different variables (i.e. stirrup or fiber percentages). These graphs are not individually represented in this report, however they were compiled into one graph to that shows the crack widths compared to load. The graph in Figure 5.1 shows a bar chart with crack width values at 100 kip load. This load is based on the 107 kip design load mentioned earlier in this report. The labels of the blue bars represent the names of the beams depending on material percentages (fiber

% _ stirrup %). For example, the yellow beam is called 00_03 because it contains no fiber percentage and 0.3% stirrups. This beam is colored yellow because it is the current standard for deep beam design set by the American Association of State Highway and Transportation Officials (AASHTO). This standard says that deep beams must contain a minimum of 0.3% rebar reinforcement and it does not require fibers. All the other beams broken during this project were compared to this beam, as seen by the black line in the graph labeled "acceptable" crack width. This black line represents the acceptable crack widths that correspond with AASHTO's standards. The red and green arrows to the side of the graph show how the crack widths are either increasing or decreasing as you move up and down the black line.

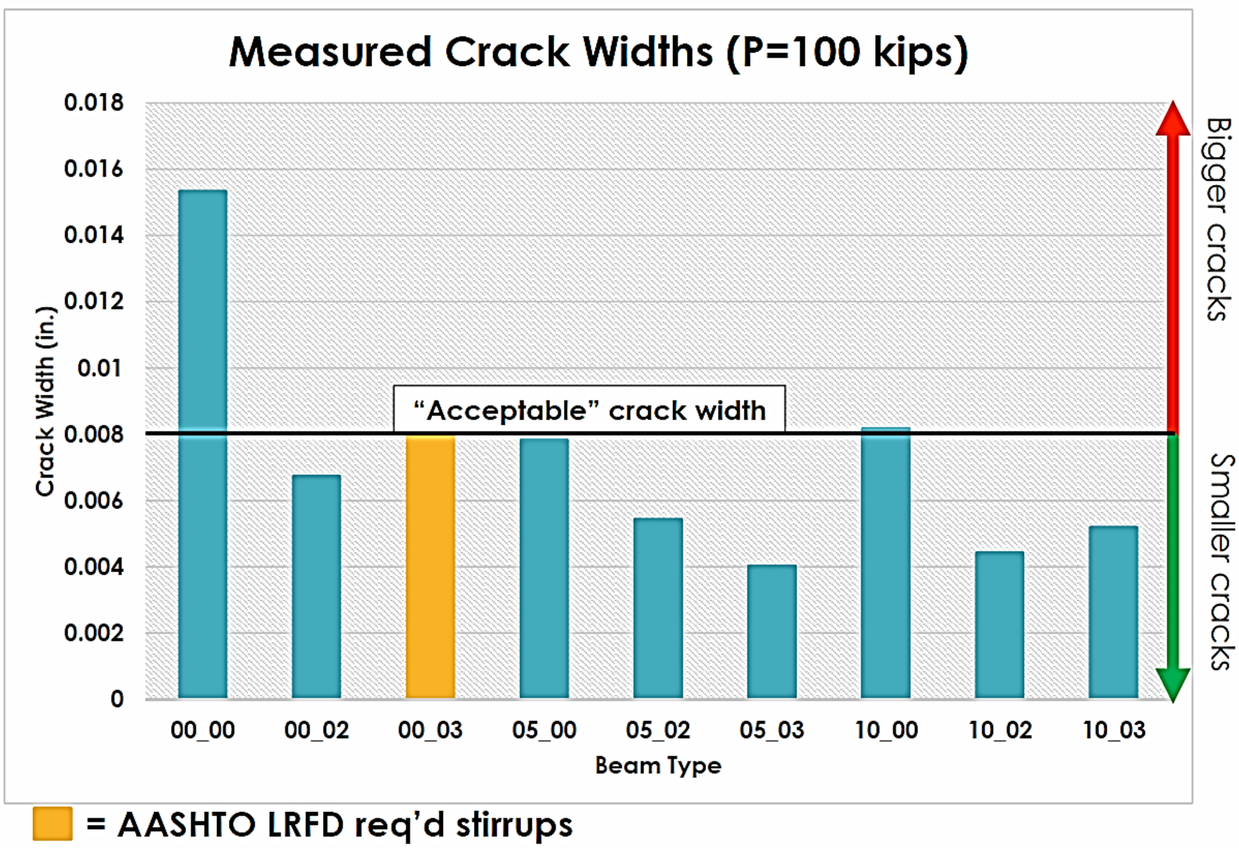

Figure 5.1: Graph of Final Results

From this graph, it can be concluded that adding fibers to the concrete mix resulted in a positive effect to decrease crack widths within deep beams because most of the blue bars are below the acceptable crack width line. There were only two bars that resulted higher than this line and those were the 00_00 and 10_00 beams. This was expected because the 00_00 beam had neither fibers nor stirrups, so the cracks had no reinforcement to control them. As for the 10_00 beam, it contained no stirrups and 1.0% fibers but the mix had too many fibers to actually help the cracks; meaning it was too fibrous so the concrete was more brittle than the other mixes.

To reiterate, the prediction for this research was that the effect of incorporating steel fibers within a concrete mix design could potentially result in smaller crack widths and a reduction in the complexity of fabrication. This was proven by reducing the amount of stirrups from 0.3% to 0.2% and 0.0%, and adding 0.5% and 1.0% fibers. Having no stirrups at all was not beneficial, but crack widths did end up being smaller when reducing stirrup percentage to 0.2% and adding fibers. Having a combination of the two reinforcements proved beneficial in this project. This means that steel reinforcement (rebar) in deep beams can be reduced and there can be an overall decrease in steel congestion. As stated in the impacts section of this report, having less steel means that there would be less labor and thus can reduce the cost of a project. Having smaller crack widths, overall, also helps bridges last longer because the internal steel would rust slower due to weathering.

6.0 Impacts

This proposed plan of study delves into a topic related to an engineer's moral responsibility for the economic longevity of infrastructure. According to ASCE's Report Card for America's Infrastructure in 2009, approximately one in twelve urban bridges and one in seven rural bridges were structurally deficient; an the backlog of deficient bridges is growing. Usually built to last 50 years, the average bridge in our country is 43 years old. Given the projected shortfall in funding, we cannot afford to conduct business as usual. If structures were built to service a community for a greater period and still maintain their strength, it would be more beneficial to the economy. Building, not only for a sense of safety and stability for the general public, but for longevity will serve governments better because it will reduce the costs of infrastructure repairs and restorations. Structures that can essentially last longer than they have in the past can also result in slower or reduced uses of resources, and less industrial waste in the environment.

7.0 Cost of Implementing Design

This research project was carried out from start to finish and a variety of costs were incurred. Table 7.1, below, shows the cost of all the materials used to construct the deep beams for this project. This table includes the cost for concrete, but it was donated by CEMEX and is not considered part of the total cost of the project.

ITEM	COST
wood	$700.00
steel	$600.00
insulating blankets	$170.00
concrete vibrator (rental)	$130.00
~~concrete~~	~~$450.00~~
steel fibers	$460.00
Bolsters	$50.00
Lifting Inserts	$20.00
travel expenses	$1,500.00
TOTAL	**$3,630.00**

Table 7.1: Costs Incurred During Implementation

8.0 Summary of Project Costs

At the very beginning of this project, a Gantt Chart, or project schedule, was created for time management. This schedule was kept throughout the course of this project and no delays occurred. A copy of this schedule can be seen in Appendix C of this report. Because this was an individual research project, one student was responsible for all the different roles of the project. These roles included: Senior engineer, designer/drafter, construction worker, lab technician, and analyst. These roles ensured that all the different aspects of this project were being managed and completed. For the first half of this project, an estimate of employee hours was provided to determine total cost of the project. This estimate is provided in table 8.1, below.

ESTIMATED HOURS SPENT ON PROJECT					
Task	**Senior Engineer**	**Designer/Drafter**	**Construction Worker**	**Lab Technician**	**Analyst**
Research	--------	--------	--------	--------	5
Design of Test Beams	--------	20	--------	--------	--------
Fabrication	30	--------	75	--------	--------
Analysis	20	--------	--------	30	40
Documentation	5	--------	--------	--------	15
Total	**55**	**20**	**75**	**30**	**60**

Table 8.1: Estimated Costs Incurred During Implementation

Table 8.2 shows the actual breakdown of man-hours provided by each position, but all were essentially performed by one person. These tables differ quite a bit in the amount of estimated per role. For example, more hours were actually spent on fabrication (construction worker) than estimated, but less were spent on analyzing data.

ACTUAL HOURS SPENT ON PROJECT					
Task	Senior Engineer	Designer/Drafter	Construction Worker	Lab Technician	Analyst
Research	3	--------	--------	--------	5
Design of Test Beams	--------	20	--------	--------	--------
Fabrication	40	--------	85	--------	--------
Analysis	5	--------	--------	38	20
Documentation	15	--------	--------	--------	25
Total	**63**	**20**	**85**	**38**	**50**

Figure 8.2: Actual Man Hours

9.0 References

*Taken from the Project Requirement section of the Dwight D. Eisenhower MIHE Transportation Fellowship Program Student Application Packet

1. Robin Tuchscherer, "Minimum Web Reinforcement in Deep Beams", *ACI Structural Journal*, V. 110, No. 2, Mar-Apr., pp. 297.

2. Dipti R. Sahoo, Carlos A. Flores, and Shih-Ho Chao, "Behavior of Steel Fiber-Reinforced Concrete Deep Beams with Large Opening", *ACI Structural Journal*, V. 109, No. 2, Mar-Apr., pp. 193.

3. Alejandra Quesada, Dwight D. Eisenhower MIHE Transportation Fellowship Program Student Application Proposal, 2013.

4. ACI 318, 2011, Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, Farmington Hills, Michigan.

10.0 Appendices

Appendix A - The Fabrication Process

Appendix B - Test Methodology

Appendix C – Gantt Chart

Appendix A-The Fabrication Process

This methodology gives a step-by-step procedure that was followed in order to properly construct the beams used in this project.

Step 1: Build Forms

This step involved building the wooden forms needed to mold and hold the concrete while it cured. It was essentially a large box with nine equally sized boxes inside. This formwork was constructed out of wood, and was dimensioned to securely fit the rebar cages mentioned in the next step.

Step 2: Build Rebar Cages

Rebar was ordered once the final design was selected. The rebar had to be manufactured to specifications and took about a week to complete and be delivered.

This step included the fabrication of the conventional steel reinforcement that was used to strengthen the beams. Beams needed to be properly dimensioned and the amount of each bar type needed to be documented and sent to the steel manufacturers to be fabricated. Nine rebar cages were tied and dimensioned as accurately as possible. 3 beams of each design were to be built. The rebar had to be properly tied and laterally reinforced to prevent from collapsing while the formwork was created.

Step 3: Placement of Concrete

CEMEX, a local concrete company, wa asked to place the concrete within the beams. On the day of the “pour”, a cement truck delivered 4 yards of concrete. 3 beams were be poured at a time. The first was simply poured using the concrete mix provided. The second batch needed to have concrete mixed with 0.5% steel fibers. The third had an amount of 1.0% fibers.

Before any concrete was poured within the forms, a portion of the concrete had to be set aside to fill cylinders. These cylinders are important to test the strength of the concrete and verify that it matched the mix design that will be provided.

The curing period took about 28 days. This duration provides the maximum strength for the concrete.

<u>Step 4:</u> Strip Forms

Forms were stripped from the beams after the curing process; this was not ideal since forms should usually be stripped a couple weeks after concrete is poured. Form release was applied to provide for an easier release and, though the beams sat in the forms longer than is recommended, they did not adhere to the wood and no cracks were caused.

Appendix B- Test Methods

<u>Step 1:</u> Break Beams

Breaking the beams will involve applying pressure to the beams until failure occurs. As the cracks form, they will be measured for thickness. This will provide the most crucial data points for the analysis of the report.

<u>Step 2:</u> Collect Data

All the measurements of the crack widths will need to be recorded and documented.

<u>Step 3:</u> Analysis

During each testing period, the crack widths of the cracks created in the beam will be measured. The beams are each expected to have varying crack widths depending on the amounts of conventional and fiber reinforcement within the beam. It is anticipated that the minimum amount of reinforcement in a deep beam may be supplemented by steel fibers. The rate of growth of the crack widths for specimens with and without fibers will be compared with one another and this relationship will be used to quantify their serviceability performance. An analysis will be done to create graphs based on the results of the testing.