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16. Abstract

Most research studies in the portland cement concrete (PCC) pavement area focused on addressing distresses related to pavement structure itself. As a result, the design and construction of other structural elements of the concrete curb and curb and gutter (CCCG) system have been overlooked and not much research has been done in this area.

Visual inspection of damaged CCCG systems was conducted in the field. All damaged CCCG systems were the TxDOT Type II system and almost all damaged CCCG systems were found at U-turn curbs due to excessive off tracking of traffic. Although geometric changes of the curb design are the fundamental solutions for the off tracking failure, such changes are not feasible in most cases due to economic and space limitations.

Extensive finite element analysis was performed based on the new U-turn curb design of the TxDOT Houston district. The horizontal loading is the most critical loading condition to evaluate the structural adequacy of a CCCG system. The structural capacity of CCCG can be enhanced by increasing the curb width and/or by inserting the curb dowel further from the traffic face of CCCG.

The use of the new U-turn curb design from the TxDOT Houston district is highly recommended for areas affected by the off tracking of heavy vehicles. It is recommended to position the curb dowel further from the traffic face of a CCCG system for better performance when the new U-turn curb design is applied. The use of an epoxy-grouted curb dowel is also recommended instead of a manually inserted straight dowel bar to ensure better bond performance between dowel bar and concrete in a CCCG system.


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# Optimized Design of Concrete Curb under Off Tracking Loads

Chul Suh
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Moon Won

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Report Date: December 2008
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Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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# Products

This report contains two products:

The improved design standards for curb and gutter are included in Appendix; and the Guidelines for Best Practices is included in Chapter 5.

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# Chapter 1. Introduction

## 1.1 Background

Over the last few decades, the construction of portland cement concrete (PCC) pavements in Texas has increased steadily. Construction of PCC pavements in urban areas presents challenges because the space available for U-turns is quite limited where the concrete curb and curb and gutter (CCCG) system is frequently provided.

Given the limited maneuvering space allowed for traffic in some urban areas, especially in large districts, long vehicles (e.g., trucks, trailers, recreational vehicles, etc.) might disturb the curbs and gutters that delineate the traveling path. Two problems that would arise include the space restriction for vehicles turning and the damage caused to curbs and gutters.

The solution to the first problem would involve the improvements in the geometric design, which is not always feasible or economically viable. However, a solution to the second problem is attainable.

## 1.2 General Practice for Curb and Gutter

Rather than being a trivial aspect of the pavement design area, CCCG could be an important feature of the whole pavement system. High quality design and construction of CCCG is especially needed in those areas where turning motorists might hit the curb unintentionally when proper maneuvering. Accordingly, these structural elements must be designed and constructed using better and more refined design standards and quality materials. Failure of the CCCG system might cause a safety problem as well as localized premature failures of the pavement.

Whether CCCG should be reinforced with steel or not is still being debated, especially in Texas and Oklahoma, where truck traffic has become an issue in some urban areas. For example, in Oklahoma, a new project was recently launched where widening a road from two to four lanes required the removal and reconstruction of curbs and gutters. Figure 1.1 shows a drilling operation for dowel bar retrofit.

Apparently, there is a need to investigate the amount of steel reinforcement and dowel bars needed in these systems, at least in areas near intersections where traffic that hits curbs could cause high level of stresses on curbs. It will be necessary to assess the magnitude of stresses imposed onto the curb and gutter system to come up with proper steel designs to prevent any structural failures.

Another case where potential problems could be avoided is shown in Figure 1.2, where the curb and gutter were constructed on King George Highway in California. This segment of the highway is located in a zone with poor drainage and where the sharp horizontal curve might cause traffic to get on the curb. The curb and gutter system doesn’t appear to have support on its back, other than the one that will be provided by the earth fill between the curb and the retention concrete wall. In this case, the gutter could be attached to the pavement with tie bars, thereby preventing the structure from tilting towards the fill area.

*Figure 1.1: Drilling holes in gutter to install dowel joints*


*Figure 1.2: Curb and gutter system prone to failure*

## 1.3 Problem Statement

In-depth review of engineering practices in the U.S., mostly state DOTs, shows that no nationwide standards exist for the design and construction of CCCG. This appears to be due to the lack of research in this area. In Texas, there is a need for improved design standards for CCCG that will resolve certain issues, primarily structural integrity of CCCG.

Given the importance of CCCG systems, it is imperative that more attention is paid to their design and construction. The current CCCG design standards of the Texas Department of Transportation (TxDOT) are fairly generic and appear to miss certain details regarding structural designs such as reinforcing steel requirements and joint details. It is known that the way CCCGs are currently designed and built is not the best and needs improvements, especially at sharp corners. In some instances, where the turning radius of a curve is quite short due to space limitations, CCCGs get hit by traffic, resulting in failures of the system.

A detailed review of current CCCG-01 standards for technical soundness and clarity was performed in this study. Also, improved state-wide design standards for CCCG systems were developed resulting in improved systems performance. From both field investigation and theoretical analysis, the technically valid information was obtained in this study.

## 1.4 Objectives

The primary objective of this research undertaking is to develop guidelines and design procedures for CCCG systems. It is anticipated that the products of this research project will enhance TxDOT engineers' ability to develop the most cost-effective strategies for design of the improved CCCG systems. The following list briefly itemizes the main objectives of this research program:

1) Summarize the findings of the literature review on the configuration of the CCCG system.
2) Evaluate the static behavior of various CCCG designs to find a proper design to prevent failure.
3) Develop improved design standards for CCCG and a guideline for best practices for CCCG systems.

## 1.5 Report Organization

This report is organized into five chapters, including the current, introductory Chapter 1. Following is a brief description of Chapters 2 through 5.

Chapter 2 summarizes the literature review on the curb configurations, while Chapter 3 presents the failure of CCCG system. Chapter 4 provides the procedures and results of the finite element analysis of the improved CCCG design. Finally, Chapter 5 provides overall summary and conclusions of this study.

# Chapter 2. Geometric Design of Curb

## 2.1 Curb Configuration

Policy on the design and use of cross-sectional highway features, including curbs, is contained in AASHTO's Policy on Geometric Design of Highways and Streets (i.e., the Green Book). The purposes of curbs are to provide drainage, delineate the edge of the pavement, support the pavement edge, provide the edge for a pedestrian walkway, and possibly provide some redirective capacity for low-speed impacts (AASHTO, 2004). On higher-speed roadways, the subject of this study, the primary function of curbs is to provide drainage, especially in the area of a bridge approach or other location where the risk of erosion is high.

Two basic types of curbs were defined in the Green Book, as shown in Figure 2.1: vertical curbs and sloping curbs. Vertical curbs usually have a vertical or nearly vertical face. Such curbs usually serve several purposes, including discouraging vehicles from leaving the road and providing drainage, walkway edge support, and pavement edge delineation.

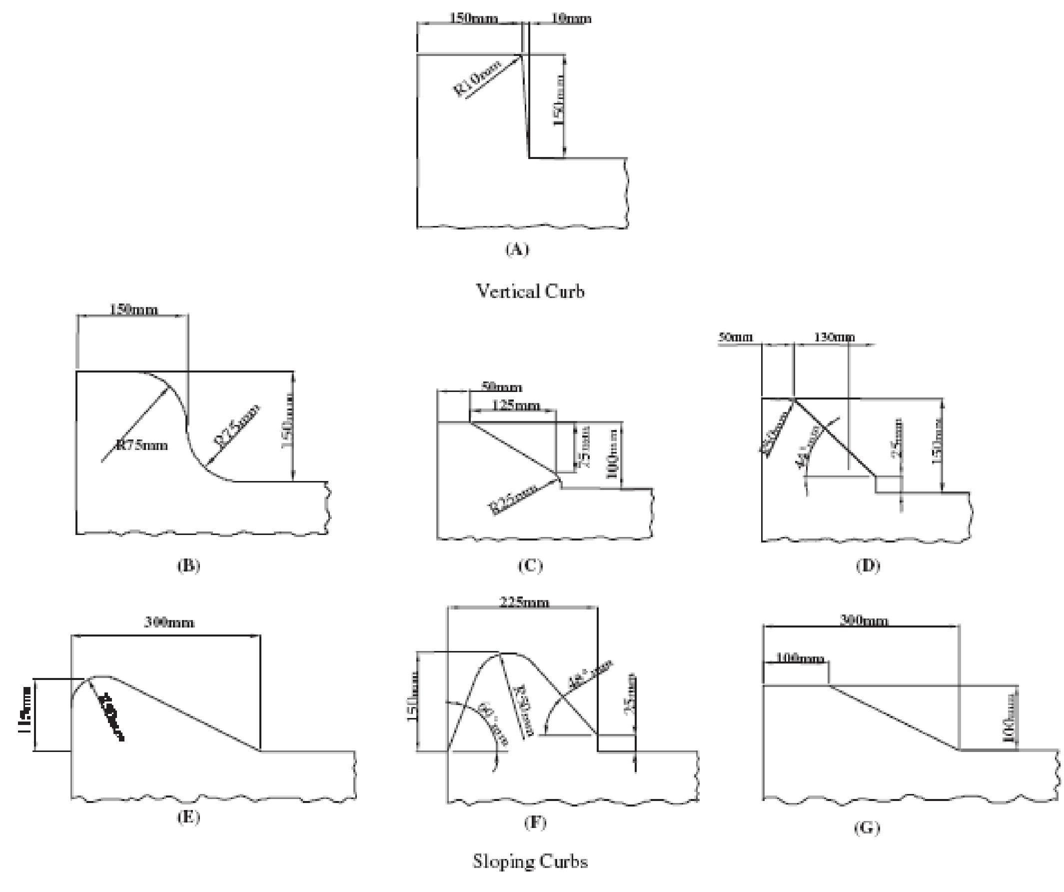



*Figure 2.1: Typical AASHTO highway curbs*

Vertical curbs have some ability to redirect errant vehicles, as the impacting wheel is steered by the curb in a direction parallel to the traveled way. If the impact velocity and angle are modest, this steering action is all that may be required to prevent the vehicle from leaving the roadway. If the speed and encroachment angle are higher, then the steering action of the curb alone is not sufficient to redirect the vehicle.

Because the vehicle center of gravity is much higher than the top of the curb, a high-speed impact with the curb will introduce a roll moment. This roll moment will in turn introduce instability into the vehicle trajectory and may even be great enough to cause the vehicle to roll over. As curbs are often used primarily for drainage purposes, they are often found in conjunction with steep side-slopes where a rollover would be even more likely. For these reasons, vertical face curbs are usually restricted to low-speed facilities where vehicles are to be discouraged from leaving the roadway.

Sloping curbs, as illustrated in Figure 2.1, have a sloped face and are configured such that a vehicle can ride up and over the curb. These curbs are designed so that they do not significantly redirect a vehicle. They are usually used in situations where redirecting a possibly damaged and out-of-control vehicle back into the traffic stream is undesirable. Sloping curbs are often used primarily for drainage purposes but are also used on median islands and along shoulders of higher speed roadways for delineation and other reasons. Sloping curbs provide drainage control while also allowing vehicles access to the roadside in emergency situations.

It is often necessary to use a curb for drainage or other reasons at a particular location that also warrants a traffic barrier. For example, approaches to bridge structures (e.g., overpasses) are often built on fills with steep slopes. An approach guardrail is required both to shield the end of the bridge railing and to shield errant motorists from the steep side slope approaching the structure. If surface water were allowed to drain from the roadway down the steep slope next to the bridge, an erosion problem could develop. A curb is usually required to channel the runoff into a catch basin or some other drainage structure. Both the curb and the traffic barrier are important functional features of the roadside in this situation (NCHRP, 2005).

## 2.2 Research on Curb Designs

The literature search conducted shows that little research work has been done in the area of structural design of CCCG. Instead, most of the research effort has focused on the safety effectiveness of curbs and the use of curbs in conjunction with traffic barriers (NCHRP, 2005).

Even though the geometric aspect of CCCG is out of the scope of this study, most of the research has been done in this area and a brief description of the findings is provided here.

Most of the current understanding of vehicle behavior during impact with curbs was developed in full-scale tests performed over 50 years ago (Beaton et al., 1953). The California Division of Highways performed 149 full-scale crash tests on 11 types of curbs in 1953 and additional tests on the 4 best-performing curbs in 1955. Similar but less extensive researches were also performed in Canada, Germany, and United Kingdom (NCHRP, 2005). The results of the California testing were used for the basis of AASHTO's design standard (AASHTO Green Book), and current TxDOT curb design follows the AASHTO design standards. Little research was performed regarding the structural capacity of CCCG system. Research in this area has shown that one of the most important characteristics of a curb is its height, which should be able to safely redirect a vehicle upon impact.

Additionally, the height of the curb should be such that the torsional moment applied by traffic loads does not exceed its ability for tilting. An analytical study conducted at the

University of British Columbia (Navin and Thompson, 1997) developed an empirical equation for dry concrete curbs as shown in the following equation:

$$h = r\left[\frac{V_r \sin\theta\left(\frac{\mu_N}{\mu_{CD}}\right)}{50}\right]^{\frac{1}{3.5}} \tag{2.1}$$

where,

$h$ is the height of the curb required to redirect the impacting vehicle,
$r$ is the radius of the tire in millimeters,
$V_r$ is the speed at redirection,
$\theta$ is the impact angle,
$\mu_N$ is the coefficient of friction of smooth rubber on test surface, and
$\mu_{CD}$ is the coefficient of friction of smooth rubber on dry concrete.

This study found that when a concrete curb exceeds the height given by Equation 2.1, then the safety of the vehicle is compromised. Another finding of the study was that the combined use of curbs and W-beam guardrails on high speed roadways was in fact a safety hazard as the vehicle could run up under the barrier.

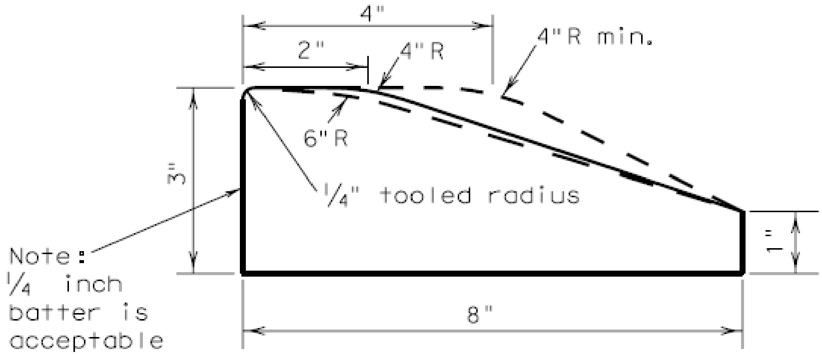
According to the Federal Highway Administration (FHWA) guidelines (FHWA, 2001), the geometry of curbs has an impact on their functionality, and therefore, the FHWA recommends curb heights as indicated in Table 2.1.

**Table 2.1: Recommended curb height based on road type**

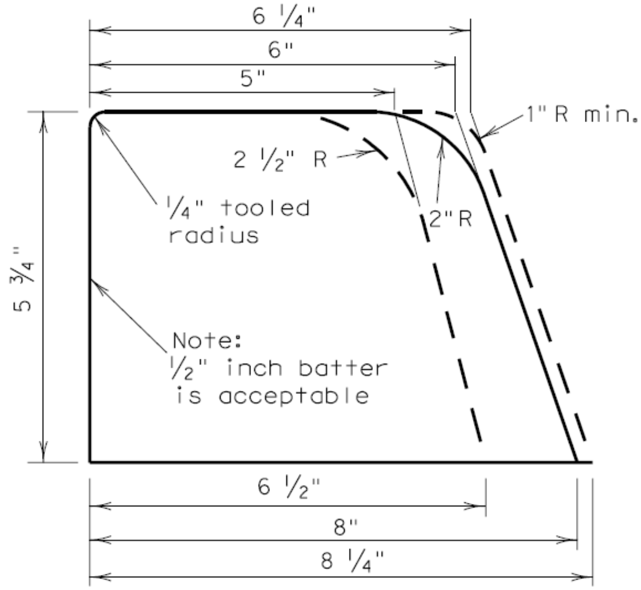
| Road Type | Max. Grade (%) Level/Roll/Mount | Cross-Slope (%) | Curb Height (in) |
|---|---|---|---|
| Urban local | Consistent w/ terrain <15.0/<8.0 | 1.5–6.0 | 4–9 |
| Rural local | 8.0/11.0/16.0 | 1.5–6.0 | n/a |
| Urban collector | 9.0/12.0/14.0 | 1.5–3.0 | 5-9 |
| Rural collector | 7.0/10.0/12.0 | 1.5–3.0 | n/a |
| Urban arterial | 8.0/9.0/11.0 | 1.5–3.0 | 5-9 |
| Rural arterial | 5.0/6.0/8.0 | 1.5–2.0 | n/a |
| Recreational | 8.0/12.0/18.0 | n/a | n/a |

## 2.3 Texas Curb Designs

Two types of curb shapes or designs are used in Texas: vertical and sloping. Vertical curbs are those that have a vertical or nearly vertical face and are usually built that way to discourage motorists from deliberately leaving the roadway. Sloping curbs are those that have a pitched face and that can usually be traversed by motorists if necessary. In general, curb height varies from 4 in. to almost 8 in. from the top of the gutter. In Texas, the height is either 3 inches or 5-3/4 inches, which are Type I or Type II curbs as shown in Figure 2.2.




(a) Type I, mono curb




(b) Type II, mono curb

*Figure 2.2: Current TxDOT concrete curb design*

## 2.4 Other Requirements for Curb and Gutter

The concrete used for the construction of curbs and gutters is usually of lower quality than that used for concrete pavement. In Item 421 of TxDOT's specifications, Class A concrete is specified for CCCG, with 3,000 psi design strength at 28 days. The maximum water/cement ratio allowed is 0.6. Whether this concrete has sufficient strength to withstand impact wheel loading needs further evaluation. For the preparation of this proposal, efforts were made to gather information on the concrete material properties and other design and construction practices required for CCCG in various state DOTs. Table 2.2 summarizes those findings. It shows that the TxDOT strength requirement is comparable to that of other state DOTs.

**Table 2.2: Summary curb and gutter features in the U.S.**

| State | Concrete Strength (psi) | EJ* Width (in) | Saw Cut | | |
|---|---|---|---|---|---|
| | | | Width (in) | Depth (in) | Spacing (ft) |
| Texas | 3,000 | 1/4-3/8 | N/A | N/A | 50 |
| City of Austin | N/A | 3/4 | N/A | 3/4 | 10 |
| Louisiana | | 1/4 | N/A | N/A | 20 |
| Alabama | 3,000 | 3/8 | 1/8 | 2 | N/A |
| Georgia | N/A | 1/2 | N/A | N/A | N/A |
| Florida | N/A | 1/2 | 1/8-1/4 | 3 1/2 | 10 |
| North Carolina | 2,500 | 1/4-1/2 | N/A | N/A | N/A |
| Virginia | 3,000-4,000[1] | N/A | N/A | N/A | N/A |
| Maryland | N/A | N/A | N/A | N/A | N/A |
| Delaware | 3,000 | ≥ 1/8 | ≥ 1/8 | ≥ 1 | 20 |
| Kentucky | 3,500 | N/A | N/A | N/A | N/A |

*EJ = Expansion Joint
[1] = for precast concrete
N/A = information not available

# Chapter 3. Failure of Curbs

## 3.1 Field Investigation

Visual inspection on damaged CCCG systems in the Beaumont district was conducted on November 2007 as shown in Figure 3.1 and 3.2. All CCCG systems were Type II. Almost all damaged CCCG systems were found at U-turn curbs; therefore, overturning truck loadings were the main cause of the damage. Failure occurred regardless of vertical tie bar spacing and joint spacing.

*(a) Overturned curb*

*(b) Vertical tie spacing = 2.5 ft*

*Figure 3.1: Overturned U-turn curbs*

*Figure 3.2: Damaged U-turn curbs in Beaumont district*

## 3.2 Off Tracking

The main cause of the failure of a U-turn curb is the low speed “off tracking.” When a vehicle makes a turn, its rear wheels do not follow the same path as its front wheels. The magnitude of this difference in path, known as *off tracking*, generally increases with the spacing between the axles of the vehicle and decreases for larger radius turns. Off tracking of passenger cars is minimal because of their relatively short wheel bases; however, many trucks off track substantially. The magnitude of the off tracking is often measured by the differences in the centerline paths of the front and subsequent axles. The maximum extent of off tracking for a turn of a given radius and length occurs at the rearmost axle or the center of the rearmost axle group.

Off tracking develops gradually as a vehicle enters a turn and, if the turn is long enough, eventually reaches what is termed *fully developed off tracking*. The off tracking does not continue to increase beyond this point for curves that are any longer. The extent of this fully developed off tracking is used to determine if the nominal lane width can accommodate the off tracking or how much the lane should be widened through the curve to accommodate the off tracking characteristics of the trucks using the highway (FHWA, 1995).

When a combination vehicle makes a low-speed turn—for example, a 90-degree turn at an intersection—the wheels of the rearmost trailer axle follow a path several feet inside the path of the tractor steering axle. This is called *low-speed off tracking*.

Excessive low-speed off tracking may make it necessary for the driver to swing wide into adjacent lanes when making a turn to avoid climbing inside curbs or striking curbside fixed objects or other vehicles. When negotiating exit ramps, excessive off tracking can result in the truck tracking inward onto the shoulder or up over inside curbs. This performance attribute is affected primarily by the distance from the tractor kingpin to the center of the trailer rear axle or axle group (FHWA, 1995).

Typical off tracking situation is illustrated in Figure 3.3 (SAE, 1992).

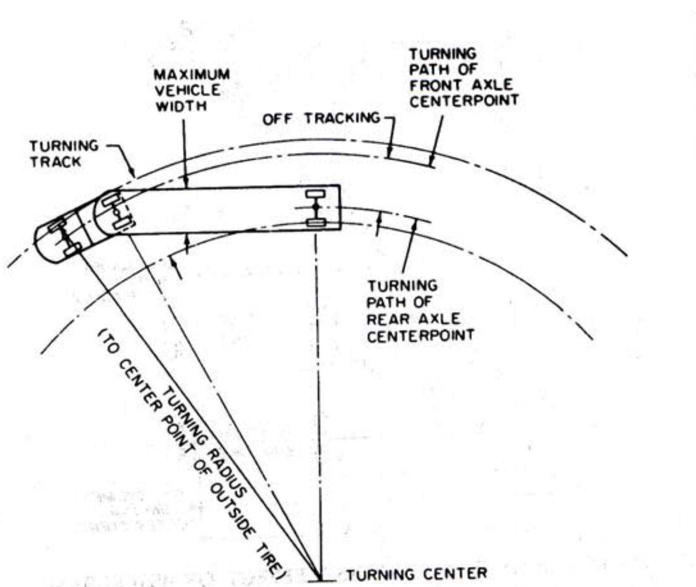



*Figure 3.3: Typical off tracking situation*

Table 3.1 demonstrates the maximum off tracking for four typical vehicles (SAE, 1992). These vehicles are illustrated in Figure 3.4.

**Table 3.1: Maximum off tracking values**

| Vehicle Type | Length | Maximum Off Tracking (ft) If Radius of Curve is: | | | | |
|---|---|---|---|---|---|---|
| | | 50 ft | 75 ft | 120 ft | 165 ft | 250 ft |
|  | 55 ft | 16.6 | 9.5 | 5.5 | 3.9 | 2.6 |
|  | 65 ft | 12.6 | 7.4 | 4.4 | 3.1 | 2.0 |
|  | 95 ft | 21.5 | 11.6 | 6.7 | 4.8 | 3.1 |
|  | 100 ft | pivoting vehicle | 19.2 | 11.1 | 7.8 | 5.0 |

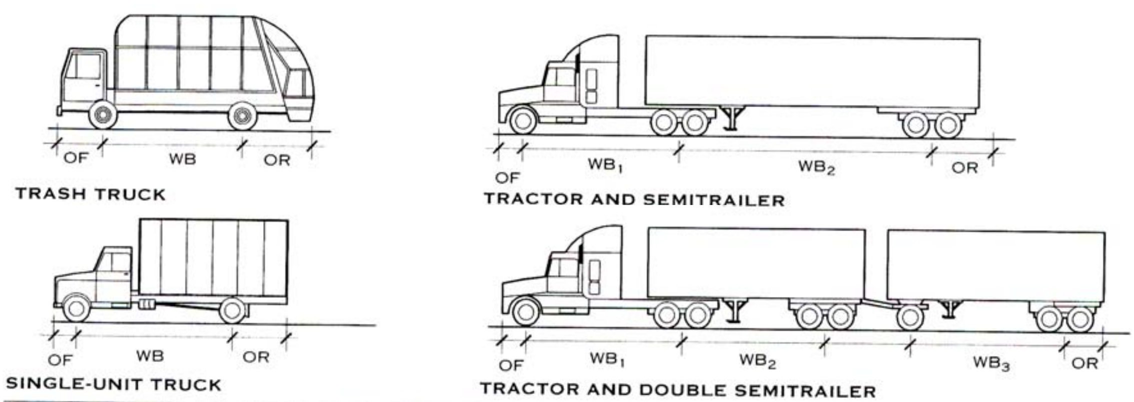



*Figure 3.4: Trucks for turning radius calculation*

Table 3.2 shows the minimum turning radius for various vehicles shown in Figure 3.4 (Ramsey, 2000).

**Table 3.2: Minimum turning radius for design vehicles (ft-in.)**

| Vehicle Type | Length | Min. Turning Radius | Outside Front Radius | Inside Front Radius | Inside Curb Radius | Curbed Lane Width |
|---|---|---|---|---|---|---|
| Trash Truck | 25’-5” | 31’-0” | 33’-0” | 21’-2” | 18’-4” | 14’-11 |
| Single Unit | 30’-0” | 42’-0” | 44’-0” | 28’-0” | 25’-0” | 20’-0” |
| WB-40 | 50’-0” | 40’-0” | 41’-6” | 19’-0” | 16’-0” | 25’-0” |
| WB-50 | 60’-0” | 45’-0” | 46’-0” | 19’-0” | 16’-0” | 30’-0” |
| WB-60 | 65’-0” | 45’-0” | 45’-6” | 22’-0” | 19’-0” | 27’-0” |

A mathematical model was developed by the FHWA to estimate geometric improvement costs for a given scenario based on the off tracking performance of the specified truck configurations, and the mileage and location of the roads on which the vehicles are expected to operate (FHWA, 1995). The model is useful in determining geometric requirements for a large range of vehicle configurations for any specified highway network. The costs to upgrade roadways to accommodate off tracking by scenario vehicles are given in Table 3.3.

These include widening the lanes for sharp curves and moving curbs back. In the worst cases, widening includes adding a lane. These costs are summarized by mainline curves, at-grade intersections, and freeway interchanges. For the two long double-trailer configurations, costs with staging areas are given in parentheses along with the costs without staging areas.

Although these geometric changes of the curb design as shown in Table 3.3 are the fundamental solutions for the off tracking failure, it is not feasible in most cases due to economic and space limitations.

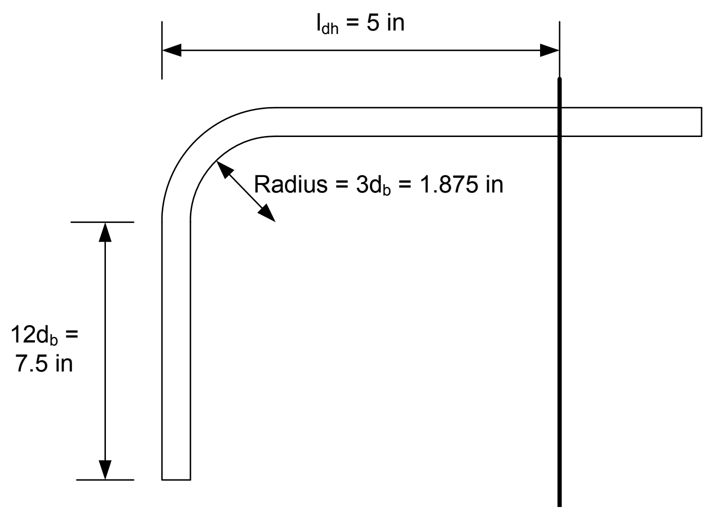
**Table 3.3: Roadway geometry cost by truck configuration**

| Truck Configuration | Trailer Length (ft) | Improvement Costs (million $) | | | |
|---|---|---|---|---|---|
| | | Mainline Curve | Intersections | Interchanges (w/ Staging Area) | Total (w/ Staging Area) |
| Five-axle Semitrailer | 48.0 (Base Line Vehicle) | 86.4 | 37.1 | 630.7 | 754.2 |
| | 53.0 | 166.2 | 128.1 | 1171.1 | 1446.0 |
| | 57.5 | 172.4 | 183.4 | 1331.6 | 1687.4 |
| Six-axle Semitrailer | 53.0 | 88.5 | 71.7 | 694.6 | 854.8 |
| Five-axle Double | 28, 28 | No additional costs are incurred; This vehicle off tracks less than the baseline vehicle. | | | |
| Seven-axle Rocky Mt. Double | 53, 28 | 136.0 | 174.0 | 1225.6 (5839.0) | 1565.5 (6149.0) |
| Eight-axle B-Train Double | 33, 33 | No additional costs are incurred; This vehicle off tracks less than the baseline vehicle. | | | |
| Nine-axle Turnpike Double | 53, 53 | 281.3 | 701.0 | 2959.7 (6913.0) | 3942.0 (7895.3) |
| Seven-axle Triple | 28, 28, 28 | No additional costs are incurred; This vehicle off tracks less than the baseline vehicle. | | | |

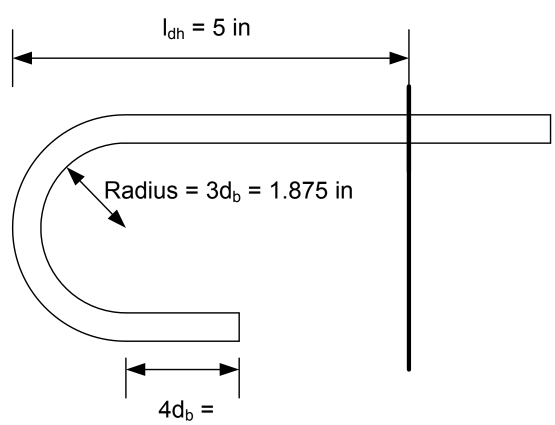
## 3.3 Curb Dowel Pullout Test

One of the critical influence factors of the curb failure is the bond strength of vertical tie (dowel) bars in the CCCG system. The pullout tests for the dowel bars installed in the CCCG system were performed in order to investigate the ultimate bond strength of the vertical dowel bars. A series of No. 5 deformed reinforcing steels were selected as the dowel bars most commonly used in the CCCG systems.

Two installation methods were investigated: 1) insertion in fresh concrete, and 2) epoxy grouting after drilling. For the fresh concrete insertion, three different types of No. 5 dowel bars were selected: straight, 90-degree hook, and 180-degree hook. For the drill and epoxy grout testing, No. 5 and No. 4 straight bars were used for comparison. Figure 3.5 presents the dimensions of ACI standard hook and the dowel bars used in this study are shown in Figure 3.6.




*(a) 90-degree hook*




*(b) 180-degree hook*

*Figure 3.5: ACI standard hooks for dowel bar pullout test*

*(a) No. 5 straight bar*

*(b) No. 5 90-degree hook*

*(c) No. 5 180-degree hook*

*Figure 3.6: Dowel bars used in pullout tests*

Figure 3.7 shows the insertion of No. 5 bars in the fresh concrete specimens, and the drill and epoxy installation is illustrated in Figure 3.8.

*(a) Insertion of 180-degree hook*

*(b) Insertion of 90-degree hook*

*Figure 3.7: Insertion of hooks into fresh concrete*

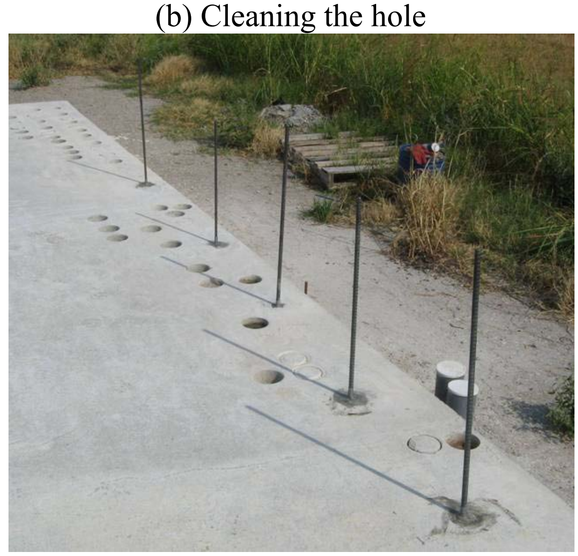
For fresh concrete bar insertion, typical paving mixture was used (water to cement ratio = 0.45), and the dimension of the concrete specimen is 24-in. by 24-in. by 10-in. The pullout tests were performed after 7 days of field curing and the corresponding compressive strength of concrete was 5100 psi.

Figure 3.8 shows the process of the installation of dowels using the drill and epoxy method. Typical 2-hr epoxy was used and the pullout testing was performed after 3 days of curing, when the epoxy grout has full strength.

(a) Drilling

(b) Cleaning the hole

(c) Epoxy injection



(d) Installation completed

*Figure 3.8: Installation of epoxy-grouted dowel*

Figure 3.9 shows the pullout test of epoxy-grouted bar in progress.

*Figure 3.9: Pullout test of epoxy-grouted bar*

The dowel bar pullout test results are presented in Table 3.4 and Figure 3.10.

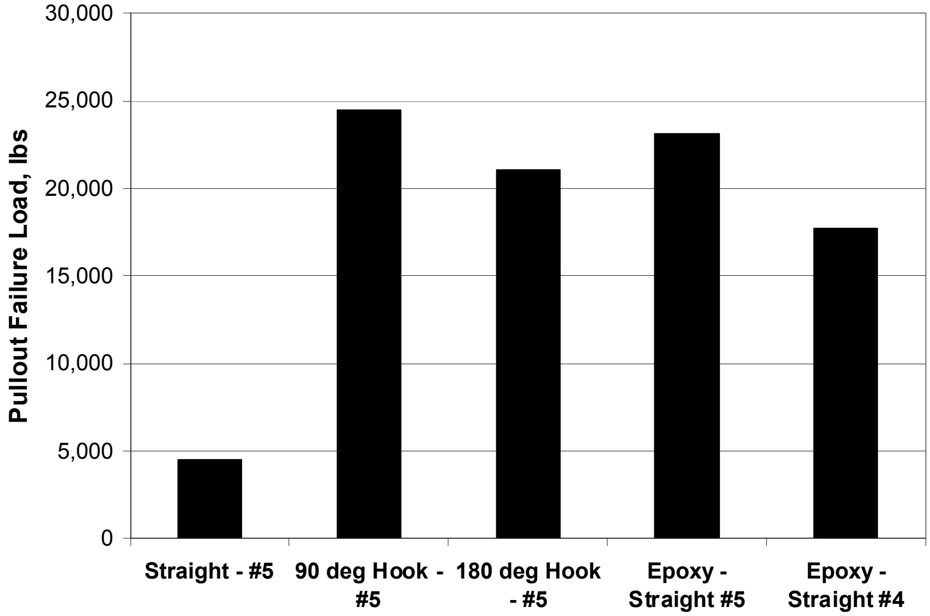
**Table 3.4: Dowel bar pullout test results**

| Dowel Type and Size | Failure Load (lbs) | Bond length (in.) | Bond Stress at Failure (psi) |
|---|---|---|---|
| Insertion: Straight – No.5 | 4513 | 5 | 575 |
| Insertion: 90-deg Hook – No.5 | 24500 | 13 | 960 |
| Insertion: 180-deg Hook – No.5 | 21100 | 11 | 977 |
| Epoxy-grouted: Straight No.5 | 23100 | 5 | 2353 |
| Epoxy-grouted: Straight No.4 | 17700 | 5 | 1803 |

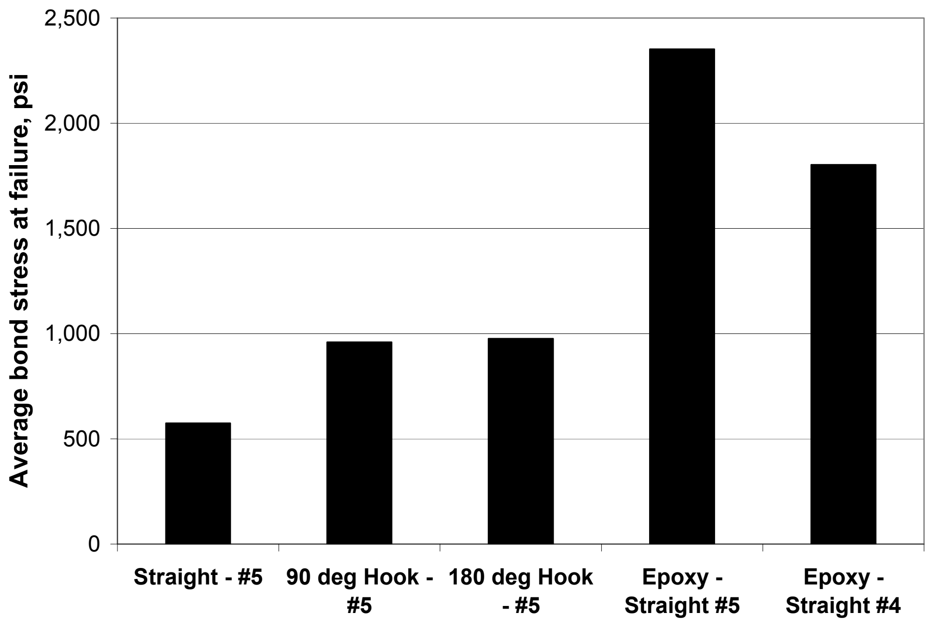
As shown in Figure 3.10 (a), the straight bar insertion in the fresh concrete has the least bond strength, while hooks and epoxy-grouted dowels have similar ultimate pullout loads. The manually inserted straight bar showed only 20–25% of pullout load compared to drill and epoxy-grouted bars.

In terms of the bond stress at pullout failure, these differences are more significant as presented in Figure 3.10 (b). The use of epoxy-grouted bars as the vertical reinforcement of the CCCG systems is the best practical, available option for the new construction of CCCG systems.

Although 90- and 180-degree hooks show similar pullout failure strengths when compared to epoxy-grouted bars, the bending of No. 5 bar is not easy and also the insertion of hooks into the fresh concrete is very difficult. Therefore, the use of epoxy-grouted dowel has the best applicability in the field condition.




*(a) Pullout failure load*



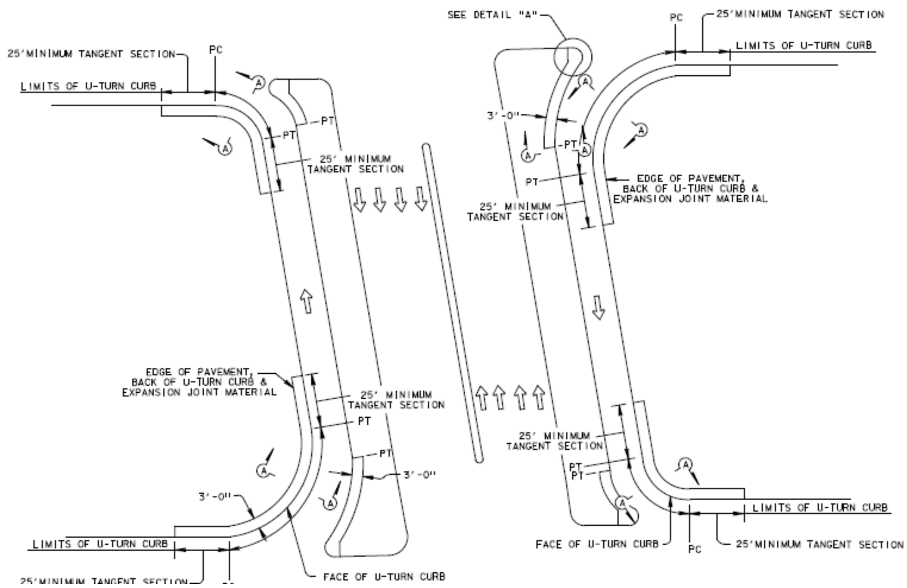

*(b) Average bond stress at pullout failure load*

*Figure 3.10: Dowel bar pullout test results*

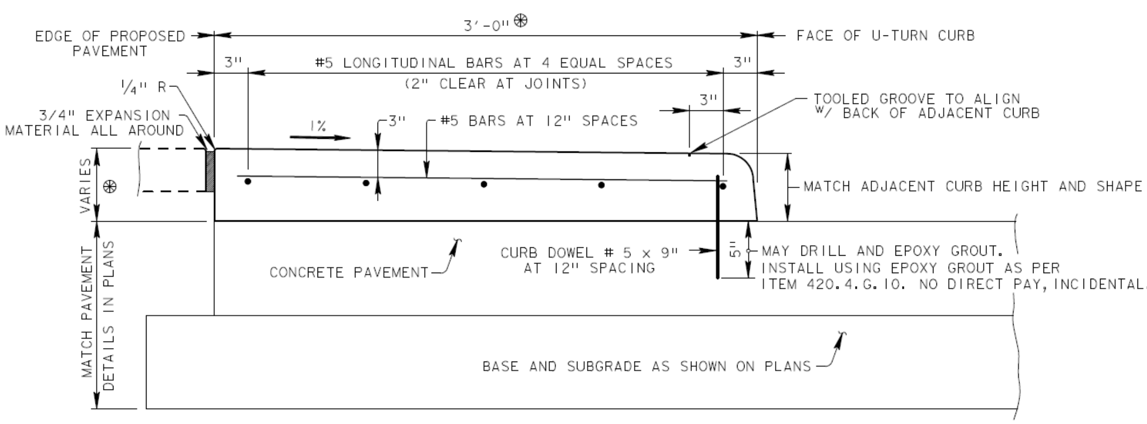
# Chapter 4. Finite Element Analysis on CCCG System

## 4.1 New U-Turn Curb Design (Houston District)

The Houston District of TxDOT developed a new design for the U-turn curbs for new construction to avoid an off tracking failure. In the new curb design, the base length of the curbs is significantly increased to strengthen the resistance to the overturning force. The new design from the Houston district is presented in Figure 4.1.




*(a) plan*




*(b) section A-A*

*Figure 4.1: New U-turn curb design from the TxDOT Houston District*

## 4.2 Overview

In this chapter, to evaluate the structural adequacy of currently designed and constructed CCCG and to develop improved design standards, the behavior of CCCG was quantitatively analyzed through parametric studies using finite element analysis. Based on the new U-turn curb design from the TxDOT Houston district as shown in Figure 4.1, a series of parametric studies were conducted for 72 cases generated from changes in three design parameters: the loading condition, the curb width, and the location of curb dowel. The critical loading condition is the most important factor in CCCG design. Also, the curb width and the location of vertical tie bar were selected as influence factors because changing these two design parameters can be the simplest and most effective way to enhance the structural capacity of CCCG.

### 4.2.1 DIANA Program (TNO, 2003)

Structural analysis was conducted with the aid of the commercial finite element analysis program DIANA (DIsplacement method ANAlyser) ver. 8.1.2. DIANA is a general purpose finite element code, based on the displacement method. It was developed by civil engineers from a civil engineering perspective in 1972. It has been under development at TNO located in Delft, the Netherlands. DIANA ver. 9.2 was recently launched. Civil, mechanical, biomechanical, and other engineering problems can be solved with the DIANA program. Its most appealing capabilities are in the fields of concrete and soil. Standard DIANA application work includes the following: concrete cracking, excavation, tunneling, composites, plasticity, creep, cooling of concrete, groundwater flow, fluid-structure interactions, temperature-dependent material behavior, heat conduction, stability analysis, buckling, phased analysis, substructuring, etc.

### 4.2.2 Geometry and Material Properties

The geometry and dimensions of a CCCG system are described in Figure 4.2. A CCCG system is made up of concrete curb, PCC pavement, and subgrade as shown in Figure 4.2. The heights of CCCG and PCC pavement (PCCP) were assumed to be 5.75 and 12 in., respectively. The width of PCCP excluding the area that is in contact with CCCG was assumed to be 72 in. Considering the symmetry, only half of a PCC pavement was modeled in the analysis. The deformed curb dowel with a diameter of 0.625 in. and length of 9 in. was assumed to be inserted into PCC pavement by 5 in.

The material properties were assumed to be linear elastic and to have the properties as follows: 1) the elastic moduli of concrete and steel are $5\times10^6$ and $3\times10^7$ psi, respectively; 2) the Poisson's ratio of concrete is 0.15; and 3) the coefficients of subgrade reaction are 150 and 300 pci for horizontal and vertical directions, respectively.

### 4.2.3 Design Parameters

Four types of loading conditions were taken into consideration as shown in Figure 4.2: the inside horizontal loading (represented by L1), the inclined loading (L2), the vertical loading (L3), and the outside horizontal loading (L4). It was assumed that the magnitude of truck impact loading is 10,000 lbf and that the loading is distributed over the whole tire width of 10 in. For vertical loading, several loading positions were assigned along the top surface of CCCG. The curb width was varied from 8 to 12, 24, and 36 in. The horizontal distance between the inner surface of CCCG and the curb dowel was varied from 4 to 8, 12, 16, 18, and 24 in. within the curb width. Table 4.1 summarizes variations of the design parameters and the indices representing 72 cases generated from changes in each influence factor.

As shown in Figure 4.1, three points are named to briefly explain the analytical results. Point A and Point C represent the outer and inner end points of the CCCG-PCCP contact area, respectively. Point B indicates the point where CCCG, PCCP, and the curb dowel meet.

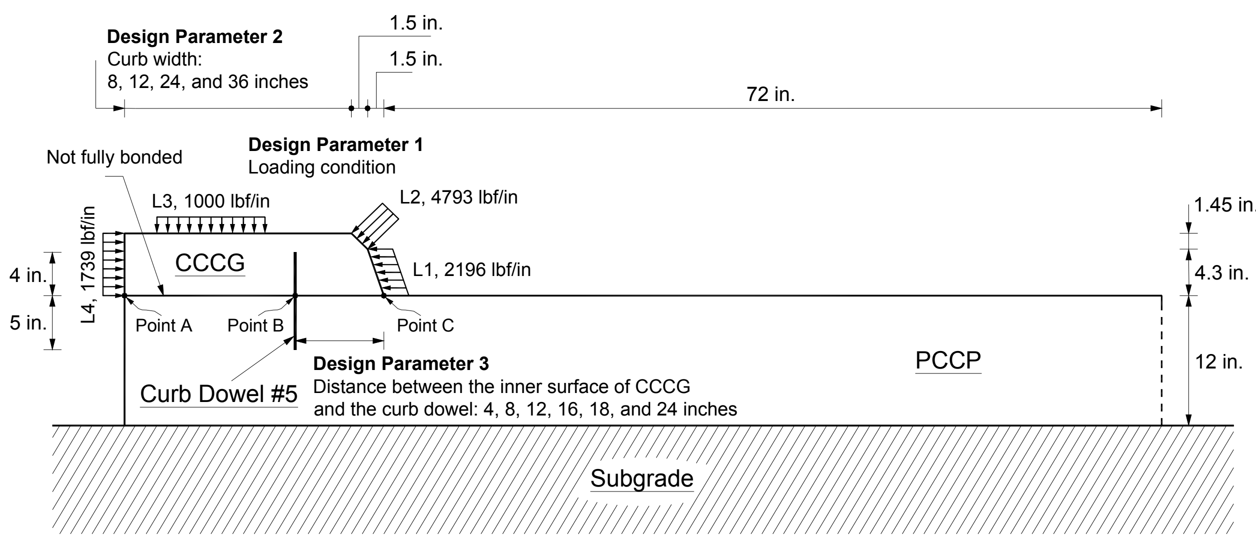



*Figure 4.2: Geometric configuration and design parameters of a CCCG system*

**Table 4.1: Variations of three design parameters**

| Curb Width (inches) | Location of Curb Dowel (inches) | Loading Condition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Inside Horizontal Loading | Inclined Loading | Vertical Loading - Distance between the loading point and the inner surface of CCCG (inches) | | | | | | Outside Horizontal Loading |
| | | | | 4 | 8 | 12 | 16 | 18 | 24 | |
| 8 | 4 | W8-D4-L1 | W8-D4-L2 | W8-D4-L31 | | | | | | W8-D4-L4 |
| 12 | 4 | W12-D4-L1 | W12-D4-L2 | W12-D4-L31 | W12-D4-L32 | | | | | W12-D4-L4 |
| | 8 | W12-D8-L1 | W12-D8-L2 | W12-D8-L31 | W12-D8-L32 | | | | | W12-D8-L4 |
| 24 | 4 | W24-D4-L1 | W24-D4-L2 | W24-D4-L31 | W24-D4-L32 | | W24-D4-L33 | | | W24-D4-L4 |
| | 8 | W24-D8-L1 | W24-D8-L2 | W24-D8-L31 | W24-D8-L32 | | W24-D8-L33 | | | W24-D8-L4 |
| | 16 | W24-D16-L1 | W24-D16-L2 | W24-D16-L31 | W24-D16-L32 | | W24-D16-L33 | | | W24-D16-L4 |
| 36 | 4 | W36-D4-L1 | W36-D4-L2 | W36-D4-L31 | W36-D4-L32 | W36-D4-L33 | | W36-D4-L34 | W36-D4-L35 | W36-D4-L4 |
| | 8 | W36-D8-L1 | W36-D8-L2 | W36-D8-L31 | W36-D8-L32 | W36-D8-L33 | | W36-D8-L34 | W36-D8-L35 | W36-D8-L4 |
| | 12 | W36-D12-L1 | W36-D12-L2 | W36-D12-L31 | W36-D12-L32 | W36-D12-L33 | | W36-D12-L34 | W36-D12-L35 | W36-D12-L4 |
| | 18 | W36-D18-L1 | W36-D18-L2 | W36-D18-L31 | W36-D18-L32 | W36-D18-L33 | | W36-D18-L34 | W36-D18-L35 | W36-D18-L4 |
| | 24 | W36-D24-L1 | W36-D24-L2 | W36-D24-L31 | W36-D24-L32 | W36-D24-L33 | | W36-D24-L34 | W36-D24-L35 | W36-D24-L4 |

### 4.2.4 Finite Element Modeling

Figure 4.3 describes the finite element mesh model of Case W8-D4-L2. The CCCG system was modeled in two dimensions for simplicity. Eight-node quadrilateral isoparametric plane stress elements with a thickness of 12 in. were used in the mesh representation of concrete. The element size varies from 1/15 to 2/5 in. Subgrade was modeled in a smeared sense by means of a linear elastic bedding with 12-inch-thick 3+3 nodes line interface elements. The curb dowel was represented by a one-dimensional truss element, which is embedded in the concrete elements as shown in Figure 4.3. The nodes of the steel element do not need to coincide with the nodes of the concrete element. The end displacements of the steel element are assumed to be compatible with the boundary displacements of the concrete element so that a perfect bond is implied.

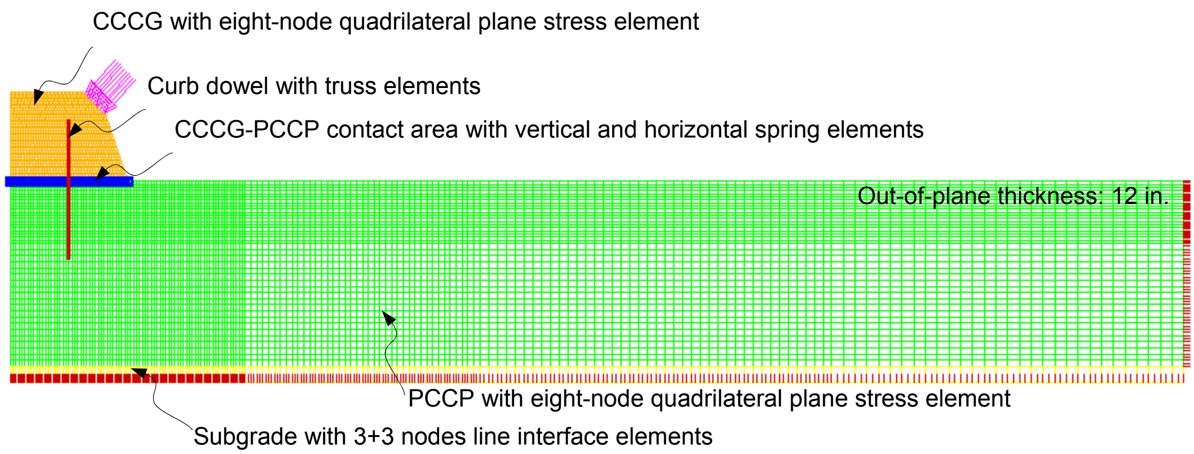


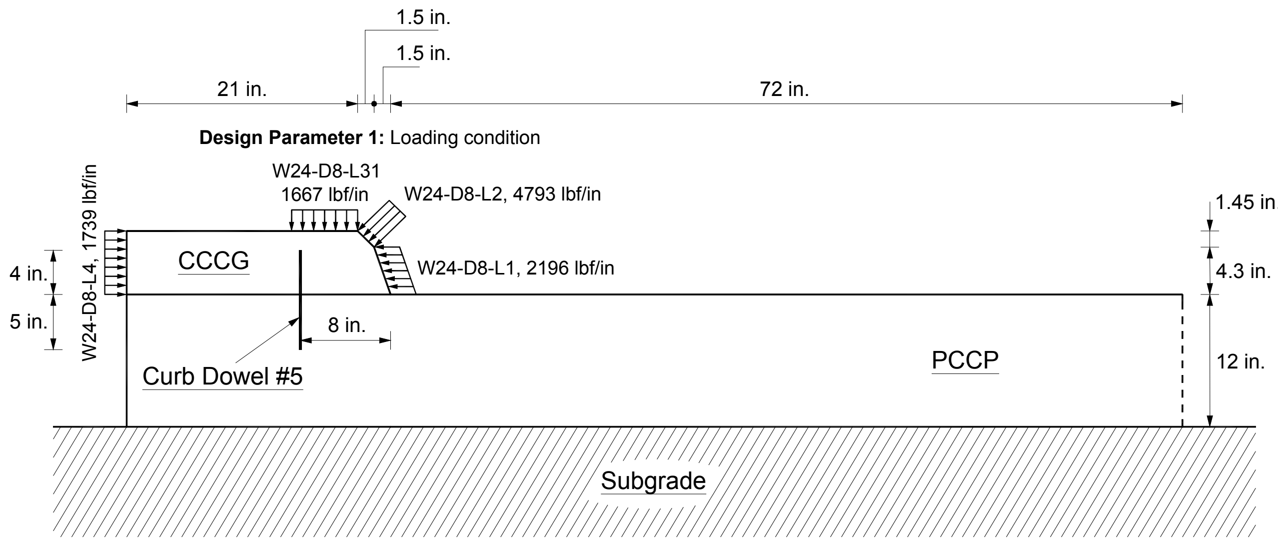

*Figure 4.3: Finite element modeling of Case W8-D4-L2*

Horizontal and vertical spring elements were placed in the area where CCCG contacts with PCCP as shown in Figure 4.3. It was first assumed that CCCG and PCCP are not in perfect bond condition that implies a possible slip between CCCG and PCCP; thus, the horizontal spring element was assumed to have relatively lower spring stiffness than concrete stiffness. The second assumption was made to model the contact condition under which CCCG and PCCP can be separated from each other; therefore, the vertical spring element was assumed to have much lower tensile stiffness than concrete stiffness. The spring stiffness was assumed as follows: (1) a tenth of concrete's stiffness is assigned to the horizontal spring; and (2) the vertical spring has a hundredth of concrete's stiffness in tension and the same stiffness as concrete in compression. A vertical constraint was applied to the bottom surface of subgrade. The cross section through the center of PCCP, namely a kind of symmetry plane, was constrained in horizontal direction.

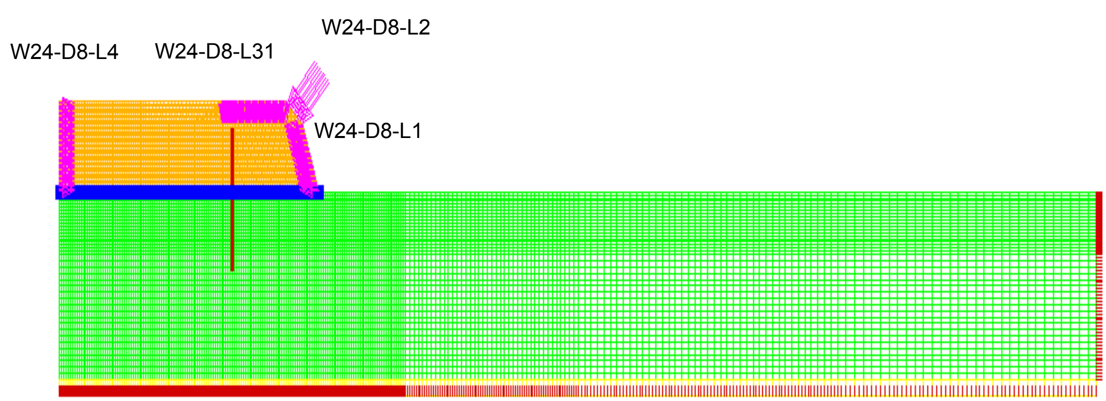
## 4.3 Analytical Results

### 4.3.1 Effect of Loading Condition

To investigate the influence of changes in loading conditions, a CCCG system subjected to four different loading conditions was analyzed as shown in Figure 4.4: Cases W24-D8-L1, W24-D8-L2, W24-D8-L31, and W24-D8-L4. The curb width was 24 in. and the curb dowel was positioned at a distance of 8 in. from the inner surface of CCCG. All of the material properties and geometric configurations were the same in all cases except the loading conditions.




*(a) Geometric configuration*




*(b) Finite element idealization*

*Figure 4.4: A CCCG system subjected to four different loading conditions*

*Deformed Shape*

Figure 4.5 shows an example of the deformed shape of the CCCG system. The CCCG system is bent upward under the loading conditions of L1, L2, and L31, while bent downward under the loading condition of L4; therefore, it is expected that tensile stresses develop on the top surface of PCCP under the loading conditions of L1, L2, and L31 and on the bottom surface of PCCP under the loading condition of L4. The loading condition of L1 results in camber as well as settlement simultaneously in the CCCG system.

As shown in Figure 4.5, the deformed shape of CCCG depends on the behavior of PCCP because CCCG is shorter than PCCP and the loading is directly applied to CCCG. The CCCG-PCCP contact area does not open when the loading has no horizontal component like the loading condition of L31. However, if the loading has a horizontal component like the loading conditions of L1, L2, and L4, CCCG is detached from PCCP; therefore, tensile stresses are expected to occur along the curb dowel and in the concrete near the curb dowel. The largest opening is observed at Point C under the loading conditions of L1 and L2 and at Point A under the loading condition of L4. The opening has the maximum values of $9.048\times10^{-4}$, $1.720\times10^{-4}$, and $3.105\times10^{-4}$ in. under the loading conditions of L1, L2, and L4, respectively.

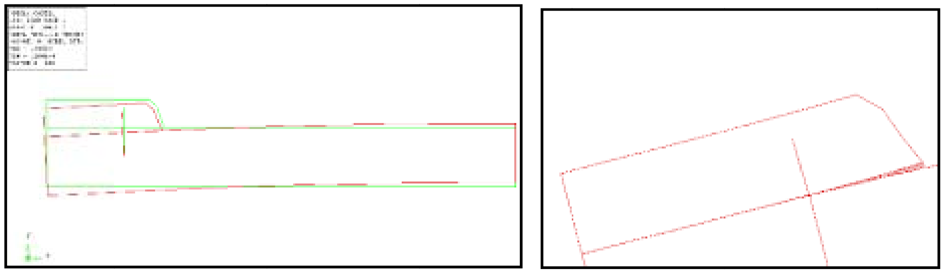
*Principal Stress of Concrete*

Figure 4.6 shows the principal stresses in the CCCG system. The principal stress in PCCP has a maximum value on the top surface of PCCP under the loading conditions of L1, L2, and L31 and on the bottom surface of PCCP under the loading condition of L4. The maximum principal stresses in PCCP reaches 718, 610, 653, and 627 psi in Cases W24-D8-L1, L2, L31, and L4, respectively. On the other hand, the maximum principal stress in CCCG occurs at Point B in all cases and has the values of 755, 500, 95, and 766 psi in each case. It can be inferred from the result that CCCG is subjected to large tensile stresses when a loading contains a horizontal component.

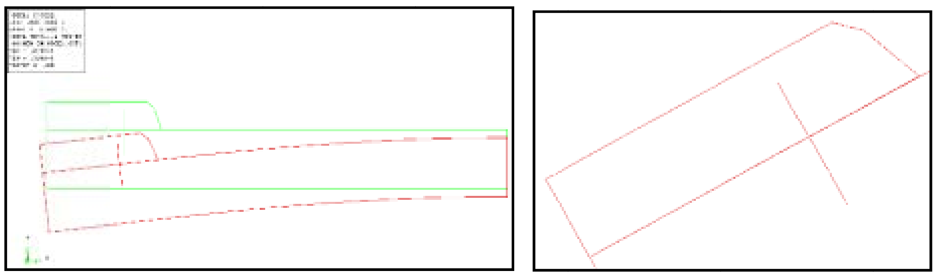
*Force along the Curb Dowel*

Figure 4.7 presents the forces in the curb dowel. When the loading has no vertical component like the loading conditions of L1 and L4, the curb dowel is subjected to tension. The maximum force develops at Point B and has the values of 172 and 374 lbf in Cases W24-D8-L1 and W24-D8-L4, respectively. This is because on the CCCG-PCCP contact area the curb dowel alone must resist the opening due to a horizontal loading. On the other hand, the curb dowel undergoes compression under the loading conditions of L2 and L31, which have a vertical component. Consequently, the loading conditions of L1 and L4 are a critical loading condition with a high likelihood of pull-out failure in a CCCG system.

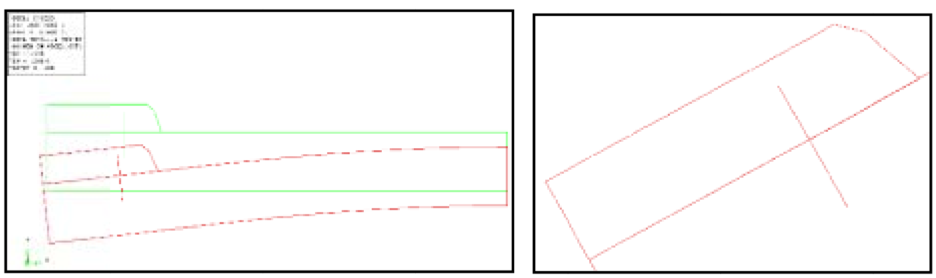
CCCG system CCCG zoom-in



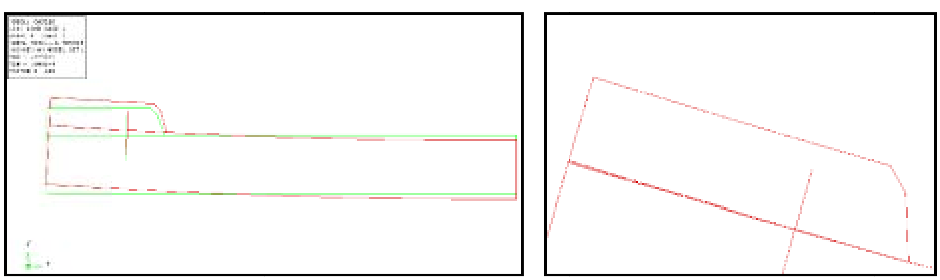
*(a) Case W24-D8-L1*



*(b) Case W24-D8-L2*



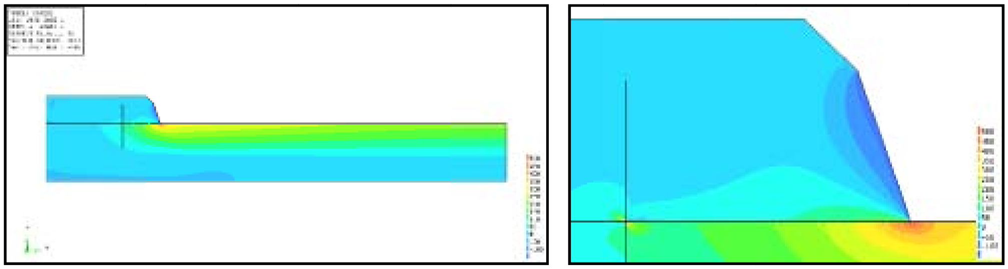
*(c) Case W24-D8-L31*



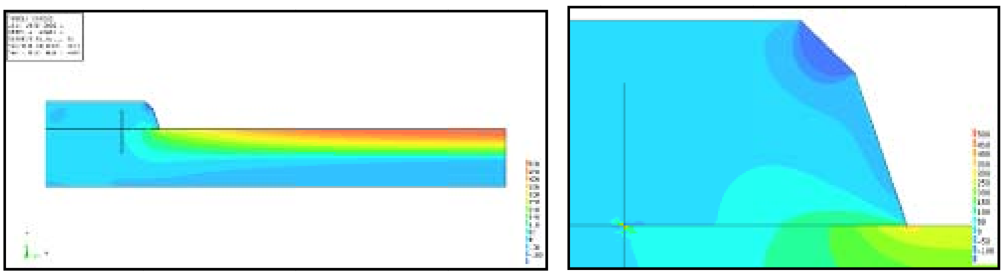
*(d) Case W24-D8-L4*

*Figure 4.5: Deformed shape of CCCG system*

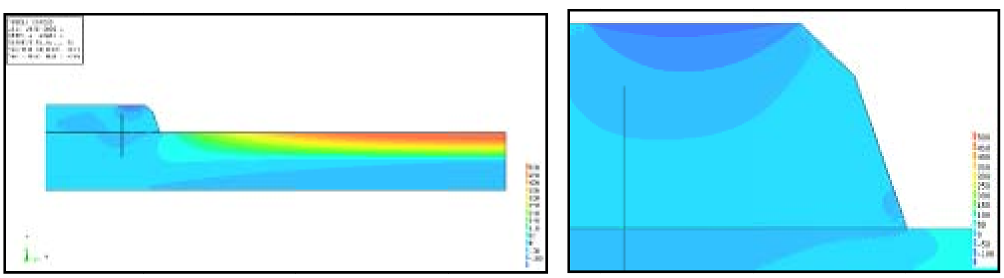
CCCG system | CCCG zoom-in



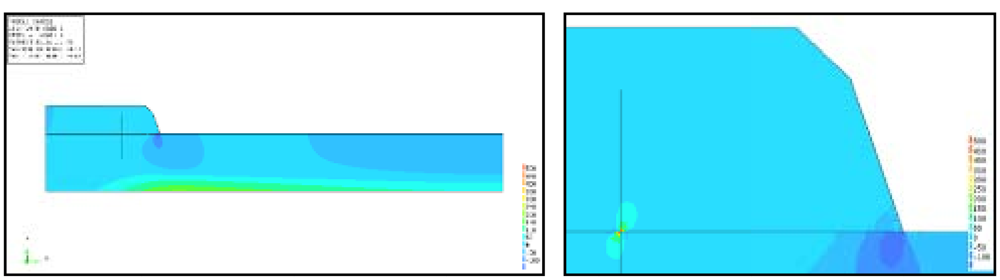
*(a) Case W24-D8-L1*



*(b) Case W24-D8-L2*



*(c) Case W24-D8-L31*



*(d) Case W24-D8-L4*

*Figure 4.6: Principal stresses in a CCCG system*

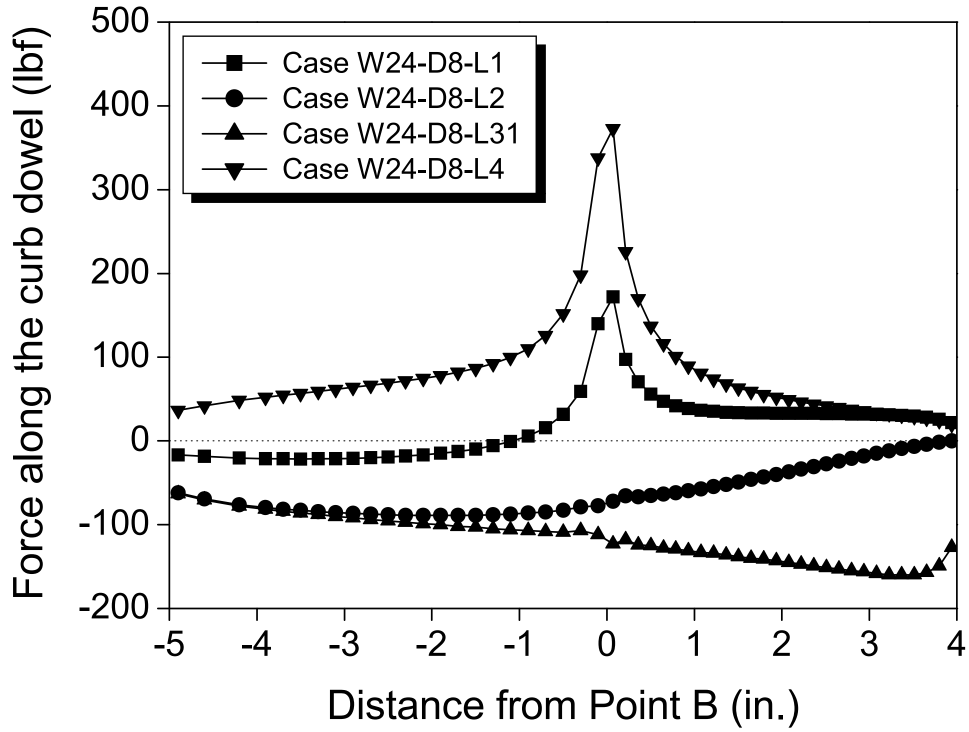



*Figure 4.7: Force along the curb dowel*

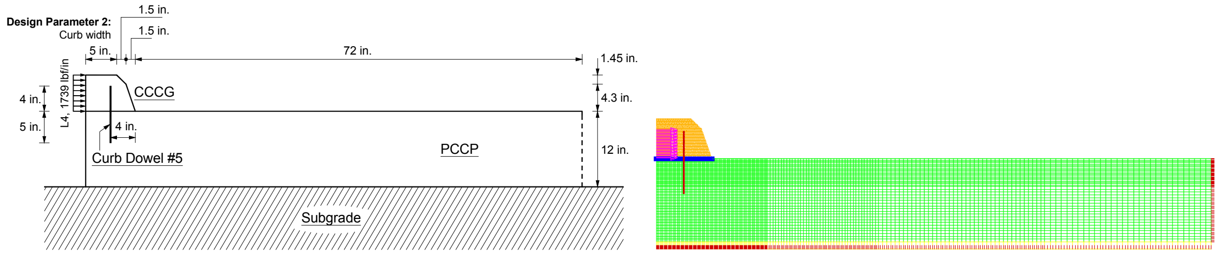
### 4.3.2 Effect of Curb Width

To examine the influence of changes in curb width, four CCCG systems with different curb widths were analyzed as shown in Figure 4.8: Cases W8-D4-L4, W12-D4-L4, W24-D4-L4, and W36-D4-L4. The curb width varied from 8 to 12, 24, and 36 in. A horizontal loading was applied on the outer surface of CCCG and the curb dowel was positioned at a distance of 4 in. from the inner surface of CCCG. All of the material properties and geometric configurations were the same in all cases except the curb widths.

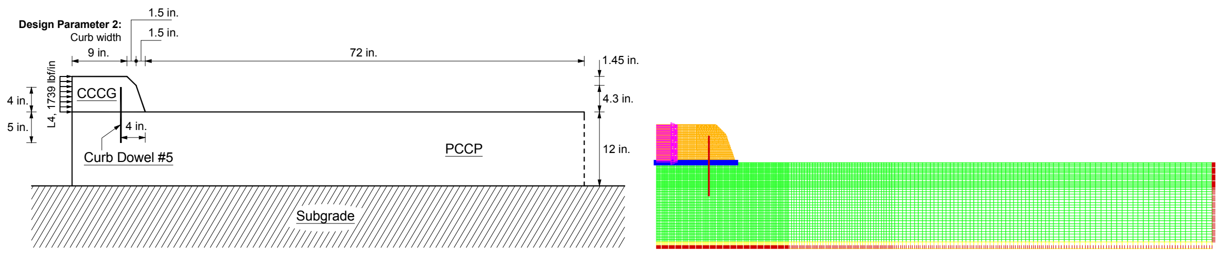
*Deformed Shape*

Figure 4.9 shows the deformed shapes of the CCCG systems. An increase in the curb width results in more upward and downward deflections. The sums of maximum upward and downward deflections are $2.830\times10^{-2}$, $2.871\times10^{-2}$, $3.008\times10^{-2}$, and $3.018\times10^{-2}$ in. when the curb width varies from 8 to 12, 24, and 36 in. The opening on the CCCG-PCCP contact area decreases overall with a larger curb width, and especially, the remarkable decrease in the opening is observed at Point A. The openings at Point A are $1.905\times10^{-3}$, $1.204\times10^{-3}$, $3.105\times10^{-4}$, and $1.221\times10^{-4}$ in. in each case. Accordingly, it is expected that a larger curb width leads to less tensile stresses in the curb dowel and the concrete near the curb dowel.

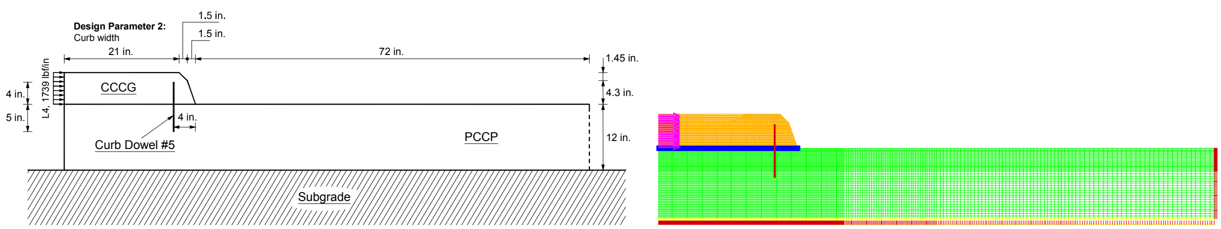
Geometric configuration | Finite element idealization



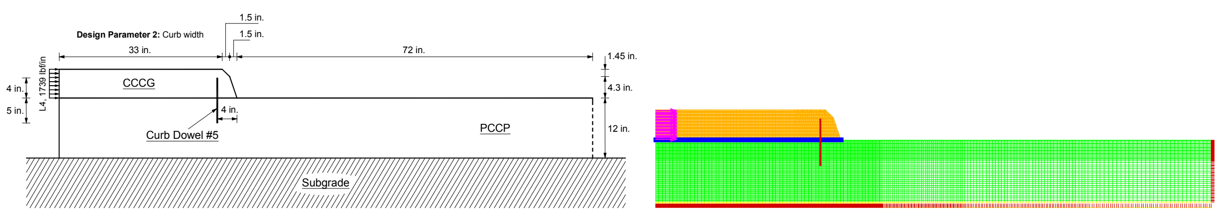

*(a) Case W8-D4-L4*




*(b) Case W12-D4-L4*



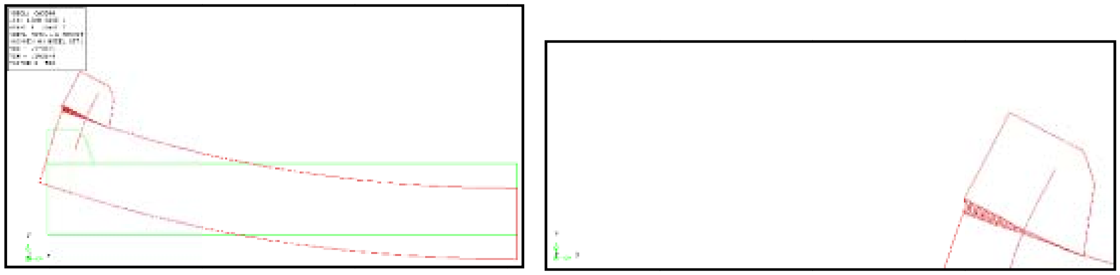

*(c) Case W24-D4-L4*



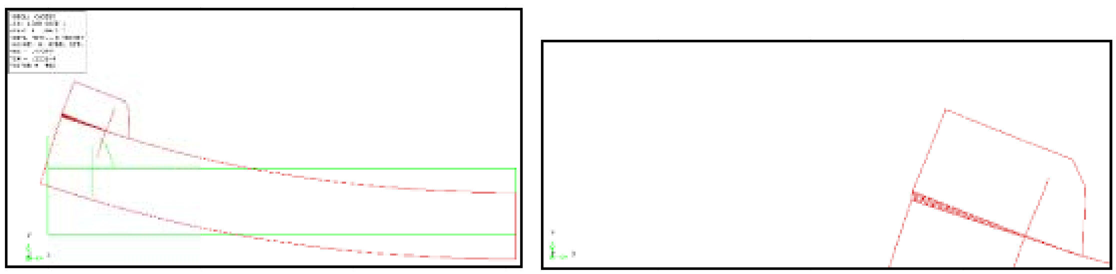

*(d) Case W36-D4-L4*

*Figure 4.8: CCCG systems with different curb widths*

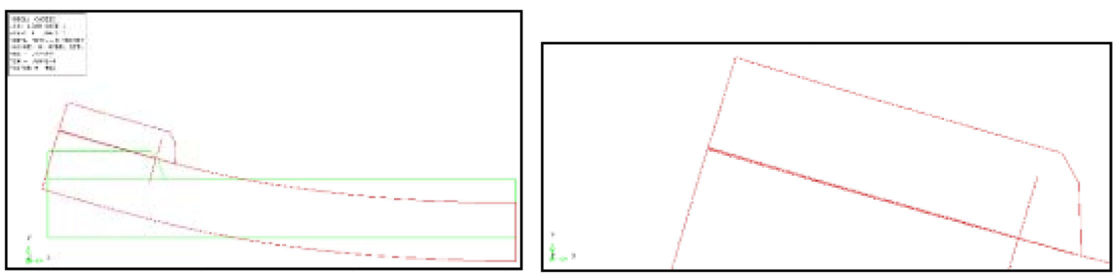
CCCG system | CCCG zoom-in



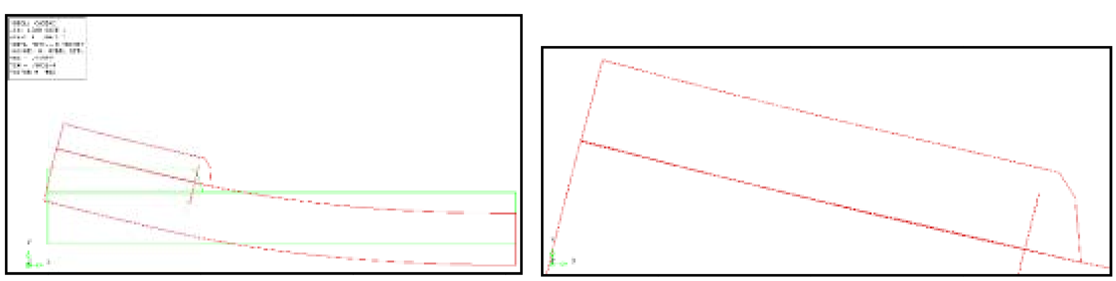
*(a) Case W8-D4-L4*



*(b) Case W12-D4-L4*



*(c) Case W24-D4-L4*



*(d) Case W36-D4-L4*

*Figure 4.9: Deformed shapes of CCCG systems*

*Principal Stress of Concrete*

Figure 4.10 shows the principal stresses in the CCCG systems. The maximum principal stress occurs at Point B in all cases and has the values of 3274, 1619, 855, and 780 psi in each case. This shows that the principal stress greatly decreases as the curb width increases. Meanwhile, tensile stresses also develop on the bottom surface of PCCP but the level is not that high, being in a range of 170 to 234 psi.

*Force along the Curb Dowel*

Figure 4.11 shows the forces in the curb dowel. The curb dowel is subjected to tension in all cases and the maximum force develops at Point B. The maximum forces reach 2003, 672, 214, and 208 lbf in each case, which shows less tensile forces and lower potential for pull-out failure with a larger curb width. However, the influence of curb width on the force in the curb dowel becomes insignificant as the curb width increases. The same goes for the deflection of CCCG system and the stresses of concrete.

### 4.3.3 Effect of Location of Curb Dowel

To evaluate the influence of changes in the location of curb dowel, four CCCG systems with different locations of curb dowel were analyzed as shown in Figure. 4.12: Cases W36-D4-L1, W36-D8-L1, W36-D12-L1, and W36-D18-L1. The curb dowels were positioned at distances of 4, 8, 12, and 18 in. from the inner surface of CCCG in each case. The curb width was 36 in. and an inside horizontal loading was applied. All of the material properties and geometric configurations were the same in all cases except the location of curb dowel.

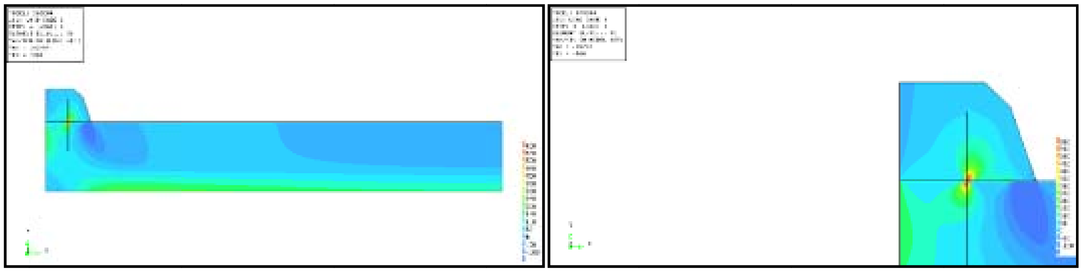
*Deformed Shape*

Figure 4.13 shows the deformed shapes of the CCCG systems. As shown in Figure 4.13, the deflection of a CCCG system is not affected by the location of a curb dowel; the maximum downward and upward deflections are $1.81\times10^{-2}$ and $8.88\times10^{-3}$ in. for all cases. On the other hand, the location of a curb dowel does affect the opening on the CCCG-PCCP contact area. The openings become $7.118\times10^{-4}$, $8.450\times10^{-4}$, $8.638\times10^{-4}$, and $8.638\times10^{-4}$ in. at Point C when the distance between the curb dowel and the inner surface of CCCG varies from 4 to 8, 12, and 18 in. Accordingly, it appears to be in Case W36-D4-L1 that the largest tensile stress develops in the curb dowel and the concrete near the curb dowel.

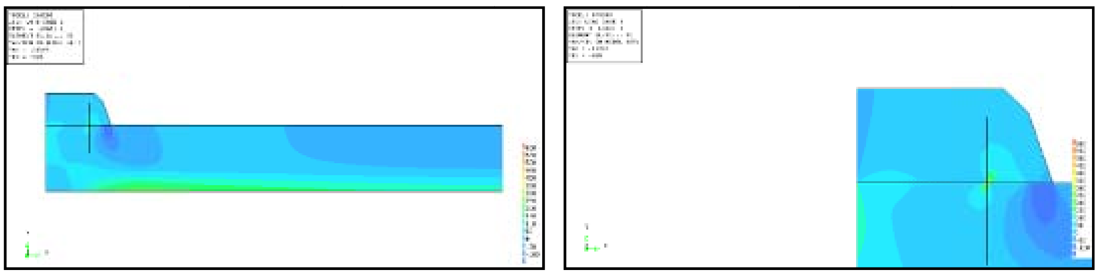
*Principal Stress of Concrete*

Figure 4.14 shows the principal stresses in the CCCG systems. The principal stress has the maximum value at Point B when the curb dowel is positioned close to the inner surface of CCCG (like Cases W36-D4-L1 and W36-D8-L1) while it has the maximum value at Point C when the curb dowel is positioned far from the inner surface of CCCG (like Cases W36-D12-L1 and W36-D18-L1). The principal stress at Point B reaches 1411, 718, 340, and 158 psi in each case, which shows that Point B exhibits a lower principal stress as the curb dowel is positioned in areas more distant from the inner surface of CCCG. At Point C, on the other hand, the principal stress is not that much influenced by the location of curb dowel, being 658, 672, 676, and 676 psi in each case.

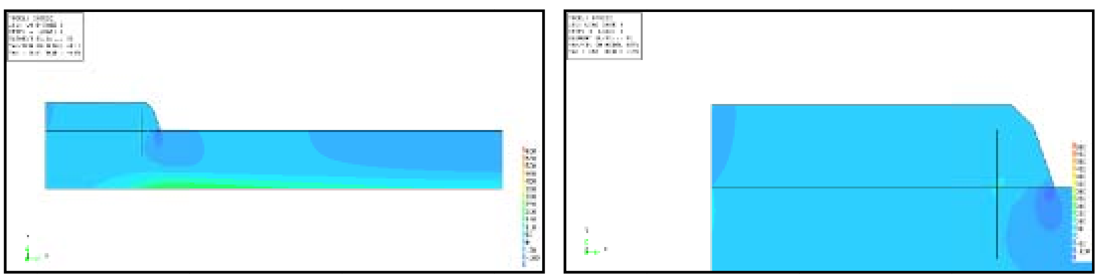
CCCG system　　　　　　　　CCCG zoom-in



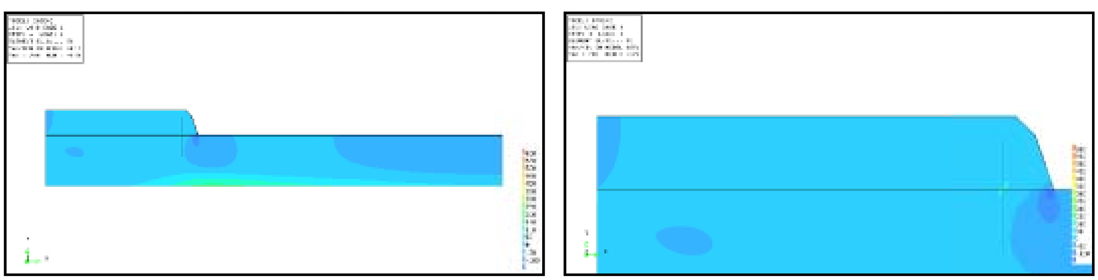
*(a) Case W8-D4-L4*



*(b) Case W12-D4-L4*



*(c) Case W24-D4-L4*



*(d) Case W36-D4-L4*

*Figure 4.10: Principal stresses in CCCG systems*

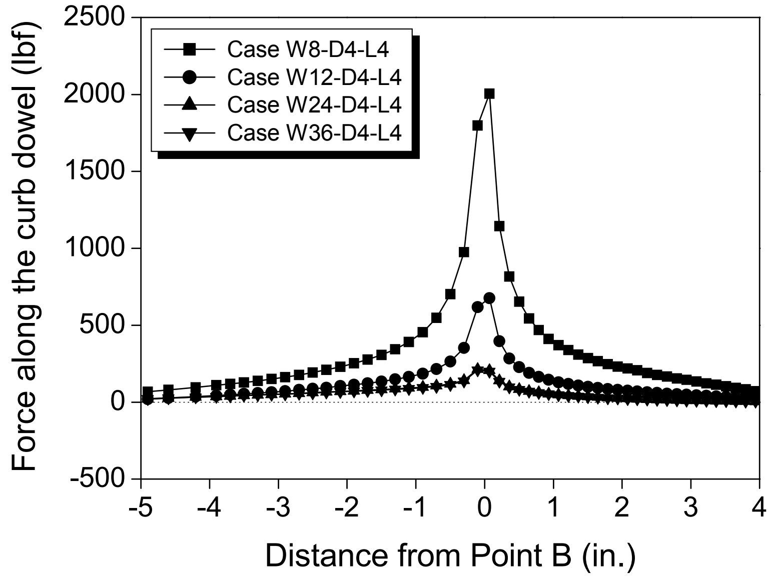
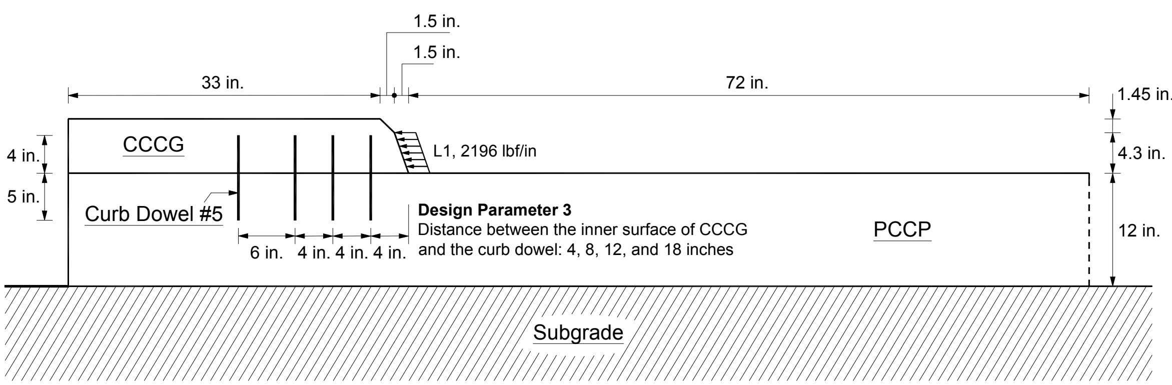
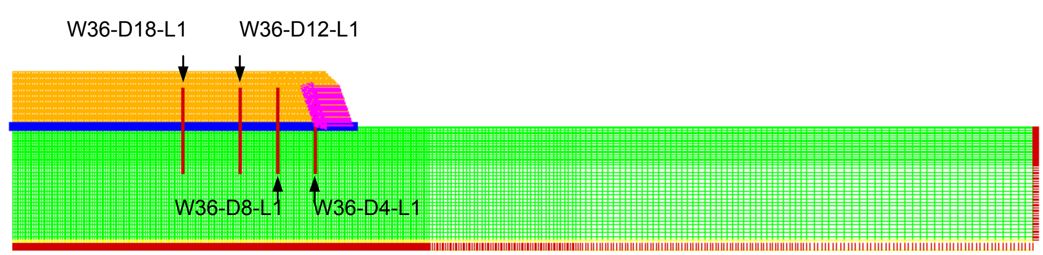



*Figure 4.11: Force along the curb dowel*



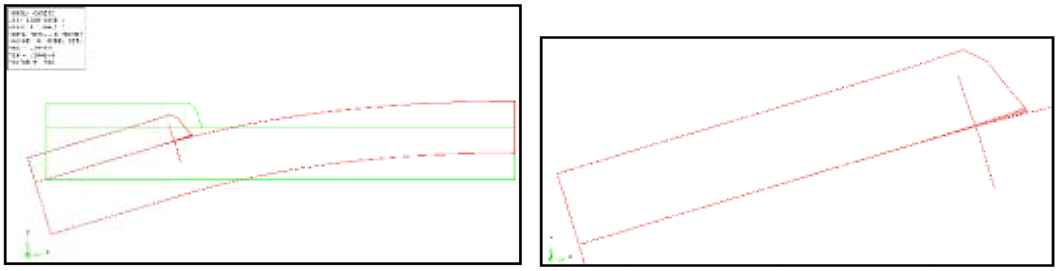

*(a) Geometric configuration*



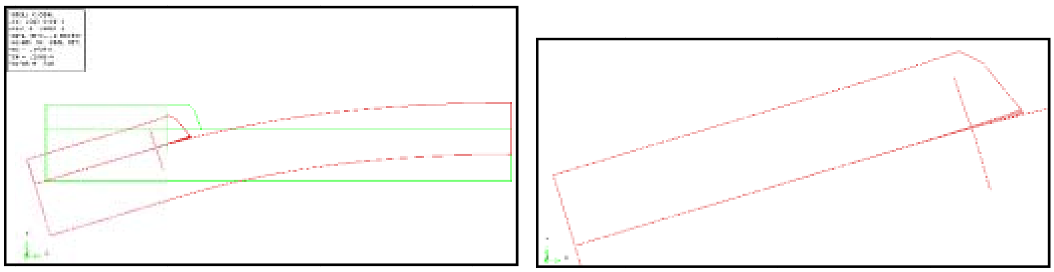

*(b) Finite element idealization*

*Figure 4.12: CCCG systems with different locations of curb dowel*

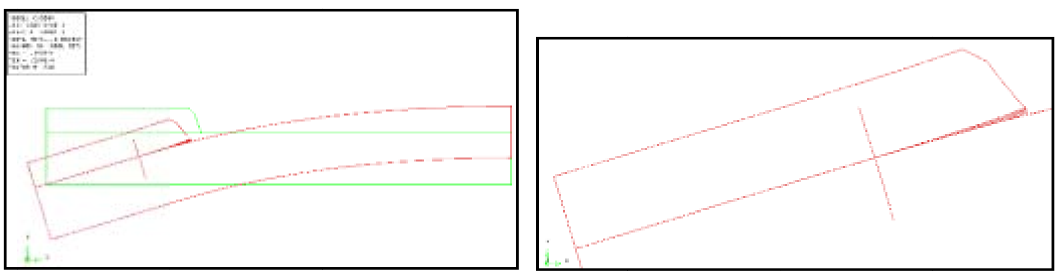
CCCG system | CCCG zoom-in



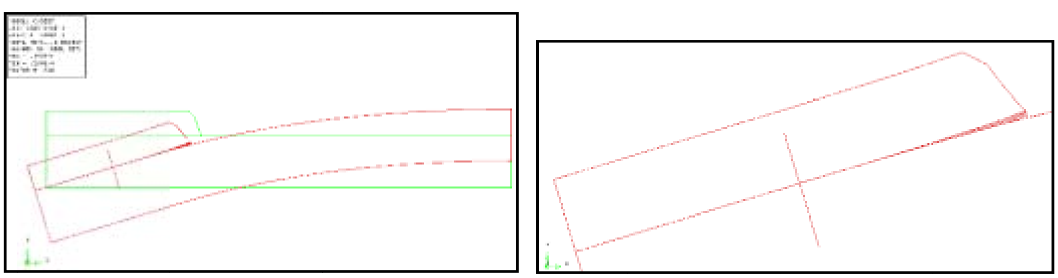
*(a) Case W36-D4-L1*



*(b) Case W36-D8-L1*



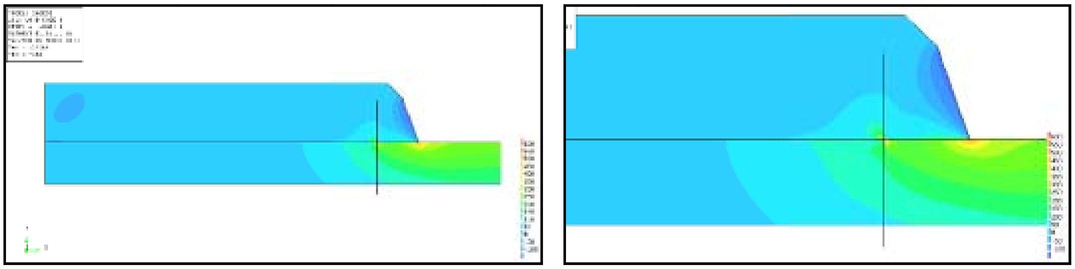
*(c) Case W36-D12-L1*



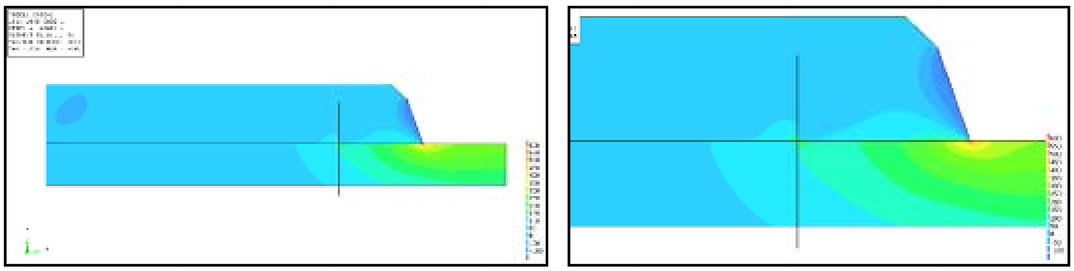
*(d) Case W36-D18-L1*

*Figure 4.13: Deformed shapes of CCCG systems*

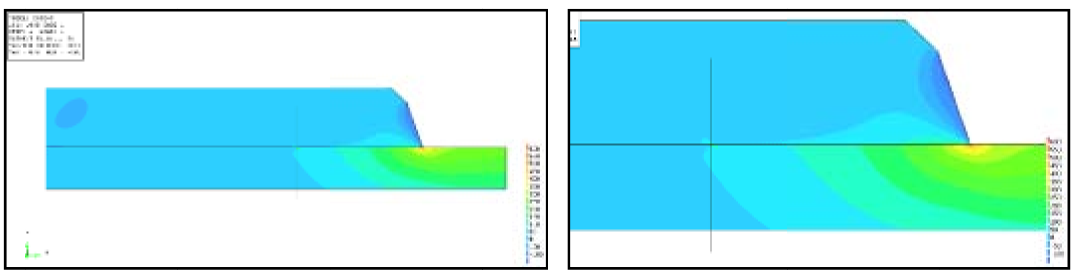
CCCG system | CCCG zoom-in



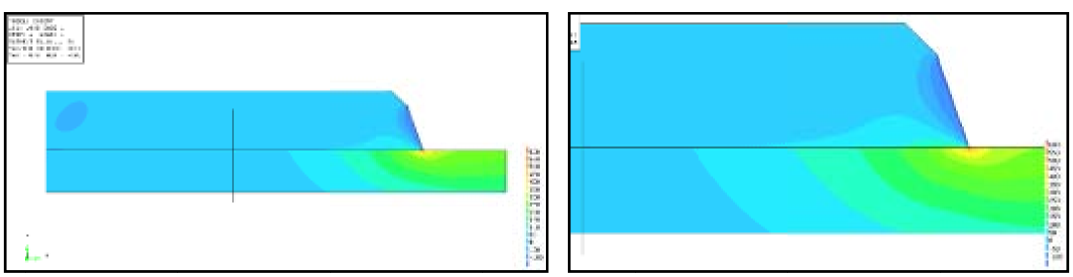
*(a) Case W36-D4-L1*



*(b) Case W36-D8-L1*



*(c) Case W36-D12-L1*



*(d) Case W36-D18-L1*

*Figure 4.14: Principal stresses in CCCG systems*

*Force along the Curb Dowel*

Figure 4.15 shows the forces in the curb dowel. In Cases W36-D4-L1 and W36-D8-L1, the curb dowel is mainly subjected to tension and has the maximum forces at Point B (488 and 170 lbf in each case). In Cases W36-D12-L1 and W36-D18-L1, on the other hand, the curb dowel undergoes compression mostly and has the maximum forces developed at the upper end of curb dowel (low as 10 and 1 lbf in each case). Accordingly, it can be inferred that the potential for pull-out failure greatly decreases as the curb dowel is positioned at distances further away from the inner surface of CCCG.

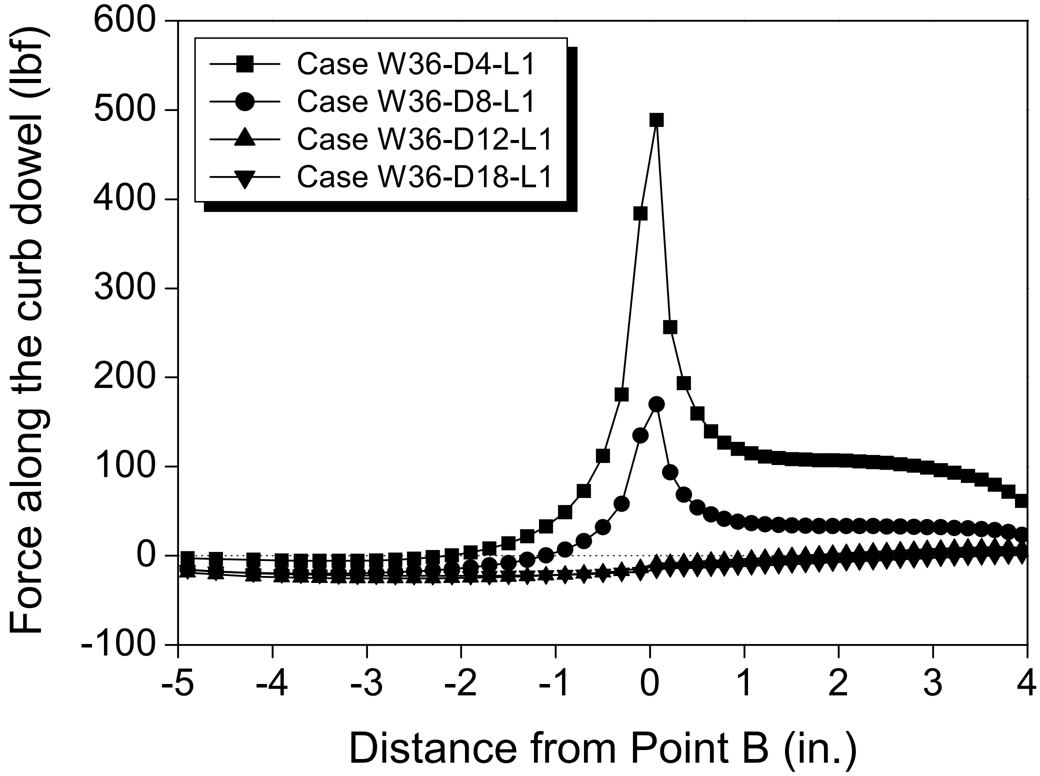



*Figure 4.15: Force along the curb dowel*

## 4.4 Summary

The maximum principal stresses in CCCG ($\sigma_{p1,max}$) and the maximum forces in the curb dowel ($F_{d,max}$) are summarized in Tables 4.2 and 4.3 with respect to the loading condition, the curb width, and the location of curb dowel. Figures 4.16 through 4.18 clearly represent variations in $\sigma_{p1,max}$ and $F_{d,max}$ according to the design parameters based on the results shown in Tables 4.2 and 4.3.

As shown in Figure 4.16, the horizontal loading (such as the loading conditions of L1 and L4) leads to high levels of $\sigma_{p1,max}$ and $F_{d,max}$, while the vertical loading (such as the loading condition of L3) results in low levels of $\sigma_{p1,max}$ and $F_{d,max}$. The position of vertical loading has little impact on the behavior of CCCG systems. Figure 4.17 shows that $\sigma_{p1,max}$ and $F_{d,max}$ decrease as the curb dowel is positioned farther from the inner surface of CCCG. However, the influence of the curb dowel location on the behavior of CCCG systems becomes insignificant if the curb dowel is positioned farther than a certain extent. As shown in Figure 4.18, longer curb width produces less $\sigma_{p1,max}$ and $F_{d,max}$ but the effectiveness of an increased curb width decreases as the curb width increases.

Given the full analysis, the following conclusions can be made:

(1) The horizontal loading is the most critical loading condition when assessing the structural adequacy of a CCCG system;

(2) The structural capacity of CCCG can be enhanced by increasing the curb width and/or by inserting the curb dowel farther from the inner surface of CCCG; and

(3) It is necessary to consider the economic efficiency and constructability when designing the CCCG system because the curb width and the location of curb dowel are limited in their ability to enhance the structural capacity of CCCG.

(4) The changes in the stress of concrete are minimal if the curb widths of CCCG exceed 24 in. In addition, the effect of the location of the curb dowel becomes insignificant when the distance between dowel and the traffic face of a CCCG exceeds 8 in.

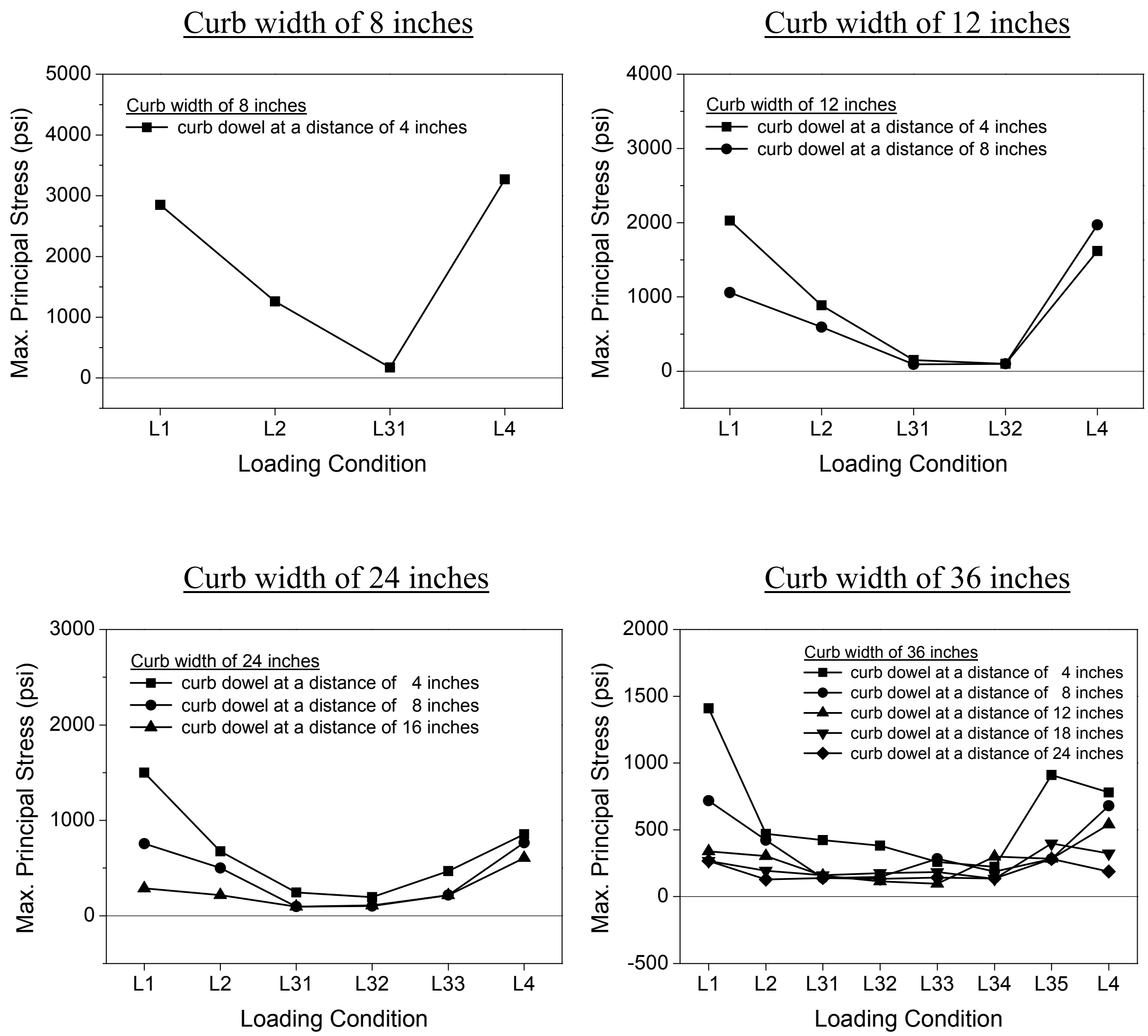
In case of the newly designed 36-inch-wide CCCG (Houston-U-CURB), the curb dowel is designed to be positioned at a distance of 3 in. from the inner surface of CCCG. In this case, the maximum principal stress becomes 1630 psi at Point B and the maximum force in the curb dowel reaches 558 lbf under the inside horizontal loading. Considering that the pull-out strength of curb dowel is 4560 lbf, the structural capacity of CCCG seems to be sufficient to prevent structural failure due to the pull-out of curb dowel. However, the actual maximum force in the curb dowel is expected to be somewhat higher than the analytical result due to the following reasons: (1) the structural analysis has been conducted on the assumption that all materials are linear elastic; and (2) the maximum principal stress exceeds the tensile strength of concrete, thereby resulting in cracking in the concrete near Point B and more loads on the curb dowel. Accordingly, it is recommended to change the location of curb dowel toward the outer surface of CCCG and to use epoxy-grouted curb dowel with high pull-out strength.

**Table 4.2: Maximum principal stress in CCCG (unit: psi)**

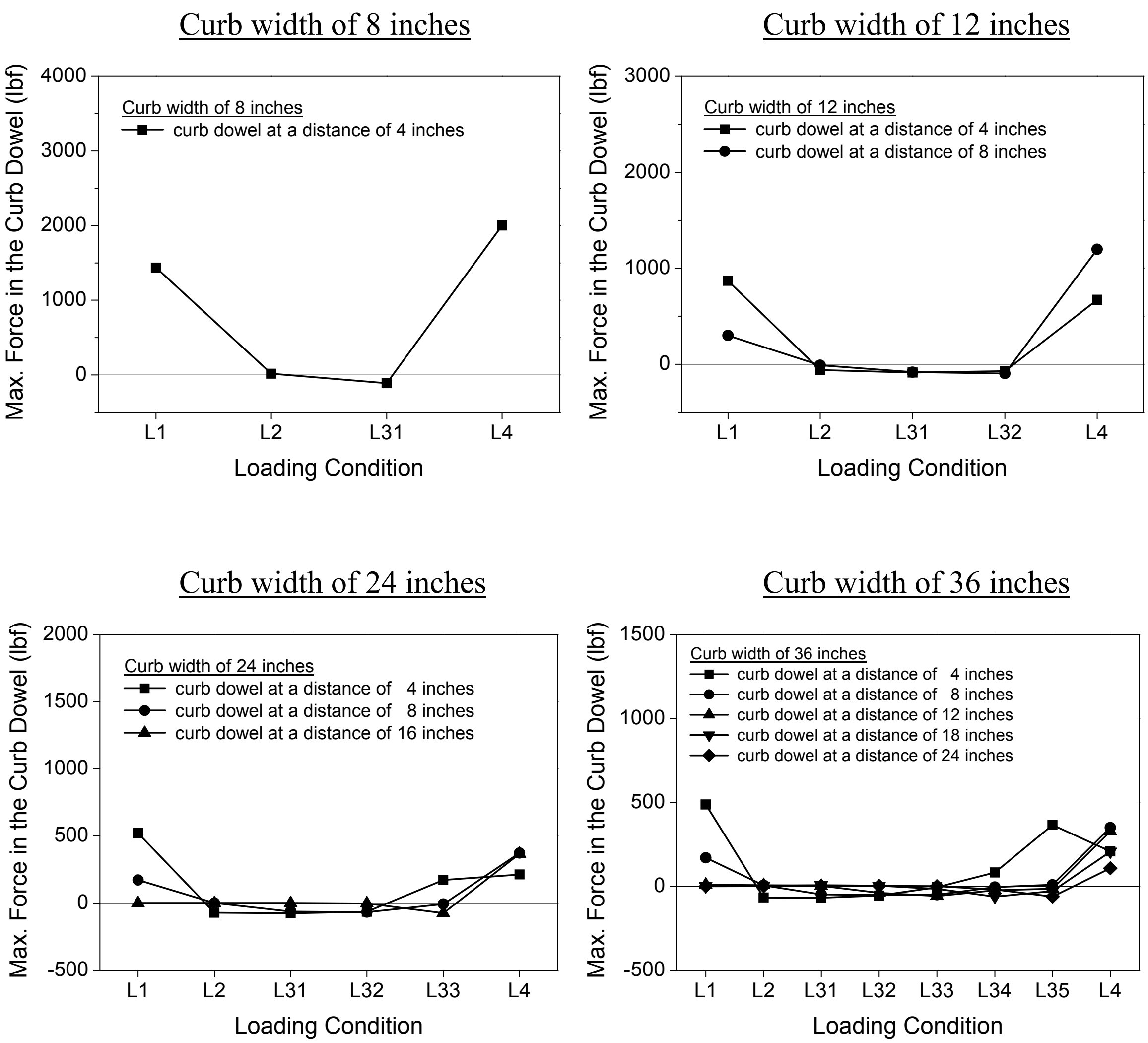
| Curb Width (inches) | Location of Curb Dowel (inches) | Loading Condition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Inside Horizontal Loading | Inclined Loading | Vertical Loading - Position of Loading (inches) | | | | | | Outside Horizontal Loading |
| | | | | 4 | 8 | 12 | 16 | 18 | 24 | |
| 8 | 4 | 2850 | 1260 | 171 | | | | | | 3274 |
| 12 | 4 | 2030 | 888 | 149 | 100 | | | | | 1619 |
| | 8 | 1060 | 595 | 91 | 100 | | | | | 1970 |
| 24 | 4 | 1500 | 675 | 244 | 194 | | 469 | | | 855 |
| | 8 | 755 | 500 | 95 | 102 | | 217 | | | 766 |
| | 16 | 288 | 217 | 95 | 108 | | 216 | | | 606 |
| 36 | 4 | 1411 | 470 | 423 | 382 | 260 | | 223 | 911 | 780 |
| | 8 | 718 | 424 | 140 | 147 | 284 | | 188 | 283 | 680 |
| | 12 | 340 | 305 | 157 | 115 | 98 | | 300 | 284 | 541 |
| | 18 | 268 | 195 | 160 | 177 | 184 | | 134 | 398 | 324 |
| | 24 | 268 | 129 | 140 | 134 | 143 | | 136 | 283 | 189 |

**Table 4.3: Maximum force in the curb dowel (unit: lbf)**

| Curb Width (inches) | Location of Curb Dowel (inches) | Loading Condition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Inside Horizontal Loading | Inclined Loading | Vertical Loading - Position of Loading (inches) | | | | | | Outside Horizontal Loading |
| | | | | 4 | 8 | 12 | 16 | 18 | 24 | |
| 8 | 4 | 1436 | 14 | -111 | | | | | | 2003 |
| 12 | 4 | 868 | -60 | -86 | -72 | | | | | 672 |
| | 8 | 300 | -10 | -83 | -97 | | | | | 1197 |
| 24 | 4 | 522 | -71 | -76 | -64 | | 172 | | | 214 |
| | 8 | 172 | 0 | -63 | -67 | | -7 | | | 374 |
| | 16 | 0 | 0 | 0 | -3 | | -74 | | | 368 |
| 36 | 4 | 488 | -67 | -68 | -55 | -5 | | 82 | 365 | 208 |
| | 8 | 170 | 6 | -48 | -51 | -50 | | -4 | 10 | 350 |
| | 12 | 10 | 7 | 3 | -38 | -57 | | -23 | -14 | 328 |
| | 18 | 1 | 5 | 7 | 4 | -15 | | -61 | -28 | 207 |
| | 24 | 0 | 2 | 3 | 3 | 2 | | -19 | -61 | 108 |

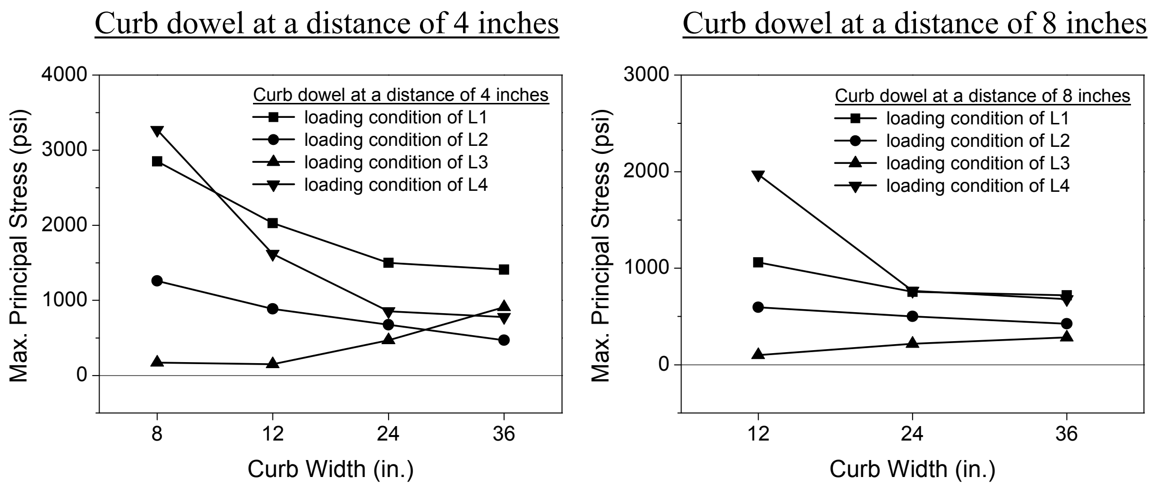



*(a) Maximum principal stress in CCCG*

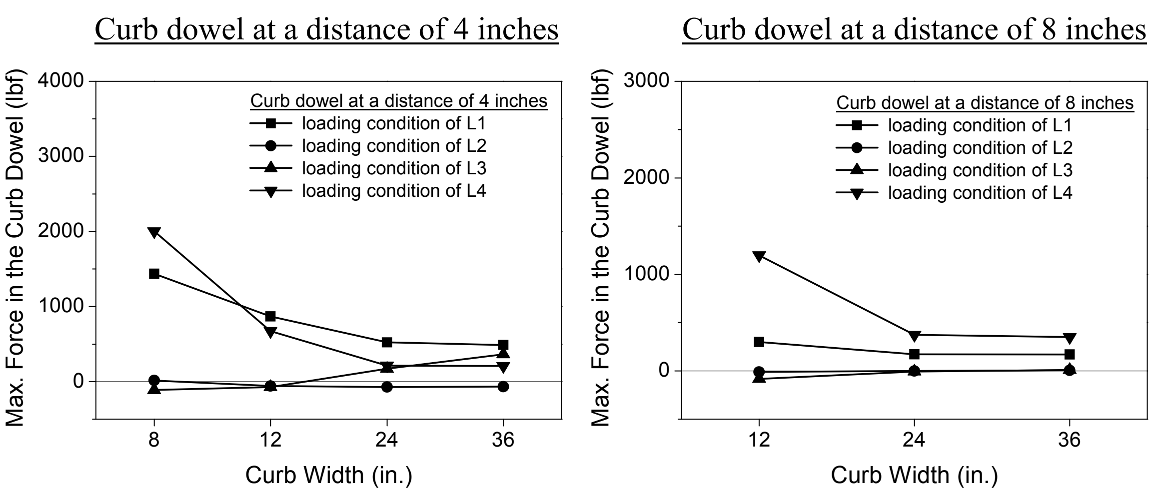



*(b) Maximum force in the curb dowel*

*Figure 4.16: Influence of the loading condition*

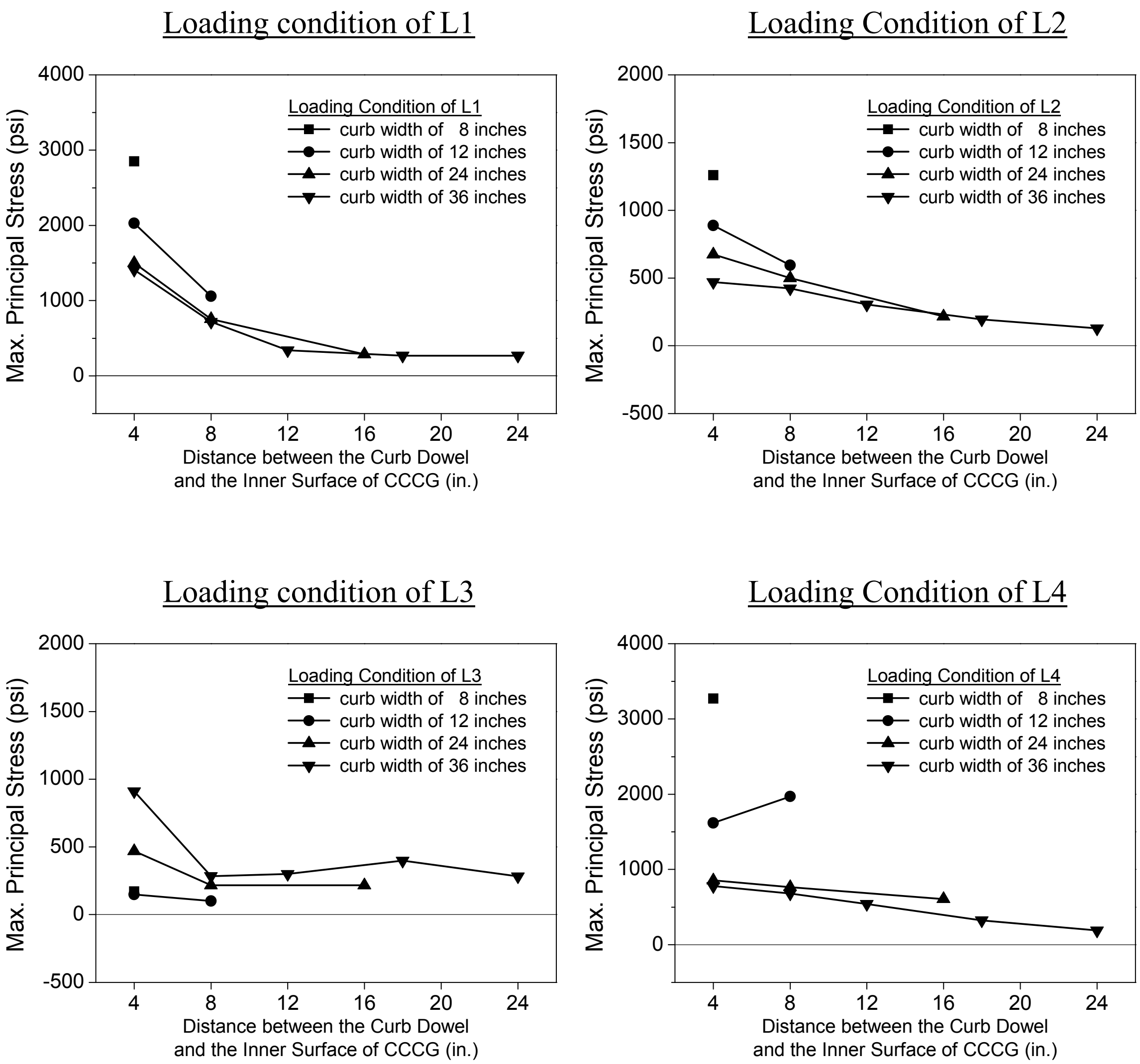



*(a) Maximum principal stress in CCCG*

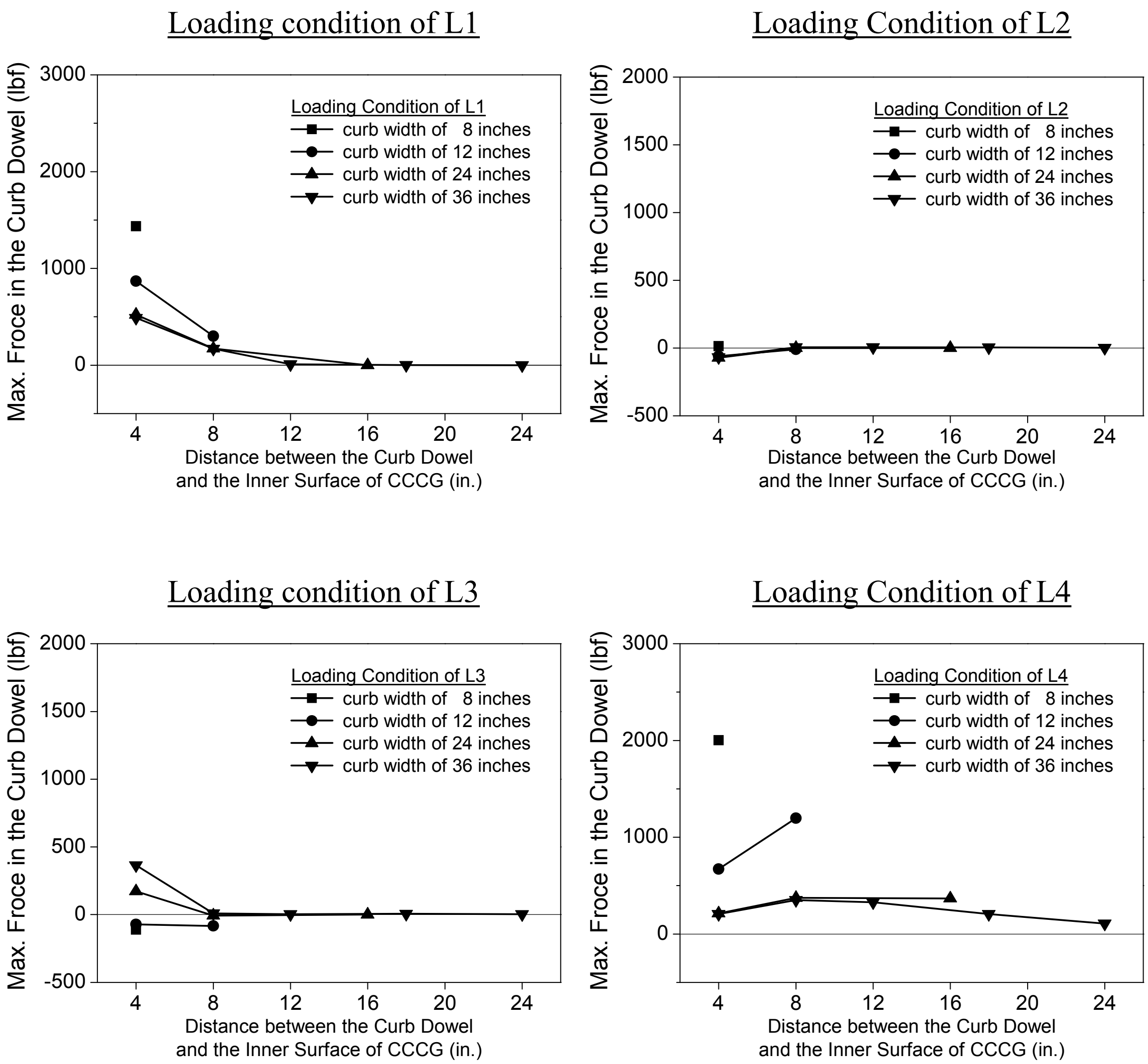



*(b) Maximum force in the curb dowel*

*Figure 4.17: Influence of the curb width*




*(a) Maximum principal stress in CCCG*




*(b) Maximum force in the curb dowel*

*Figure 4.18: Influence of the location of curb dowel*

# Chapter 5. Conclusions and Recommendations

This chapter provides a summary of the work undertaken over the course of this study. Also presented in this chapter are recommendations for TxDOT in the design of a CCCG system. The following conclusions are made on the basis of the results of this study.

1) Most research studies in the PCC pavement area focus on addressing distresses related to pavement structure itself. As a result, the design and construction of other structural elements of the concrete curb and curb and gutter (CCCG) system have been overlooked and little research has been done in this area.

2) The literature search conducted shows that little research work has been done on CCCG structural design. Instead, most of the research effort has focused on the safety effectiveness of curbs and the use of curbs in conjunction with traffic barriers.

3) Visual inspection of damaged CCCG systems was conducted in the field. All damaged CCCG systems were the TxDOT Type II system and almost all damaged CCCG systems were found at U-turn curbs. It is concluded that the off tracking of truck loadings was the main cause of the curb damage. Failure occurred regardless of vertical tie bar spacing and joint spacing.

4) The FHWA's cost calculation model to upgrade roadways to accommodate off tracking includes widening the lanes for sharp curves and moving curbs back. Although these geometric changes of the curb design are the fundamental solutions for the off tracking failure, it is not feasible in most cases due to economic and space limitations.

5) The pullout tests for the dowel bars installed in the CCCG system were performed in order to investigate the ultimate bond strength of the vertical dowel bars. The manually inserted straight bar into the fresh concrete showed the least bond strength; the drilled and epoxy-grouted dowels showed the best performance in terms of bond strength. The use of epoxy-grouted bars as the vertical reinforcement of the CCCG system is the best practically available option for the new construction of CCCG systems.

6) Extensive finite element analysis was performed based on the new U-turn curb design of the TxDOT Houston district. Three design parameters were considered for calculations: the loading condition, the curb width, and the location of curb dowel.

7) From the results of finite element analysis, the following conclusions can be made:
   a. Horizontal loading is the most critical loading condition when assessing the structural adequacy of a CCCG system.
   b. The structural capacity of CCCG can be enhanced by increasing the curb width and/or by inserting the curb dowel farther from the inner surface of CCCG.

c. It is necessary to consider economic efficiency and constructability when designing the CCCG system because the curb width and the location of curb dowel are limited in their ability to enhance the structural capacity of CCCG.

d. The changes in the concrete stress are minimal if the curb widths of CCCG exceed 24 in.

e. The effect of the location of the curb dowel becomes insignificant when the distance between dowel and the traffic face of a CCCG exceeds 8 in.

Based on the research efforts in this study, the following recommendations are proposed. These recommendations could be used as guidelines for the new construction of CCCG systems for the areas experiencing off tracking load conditions.

1) The use of new U-turn curb design from the TxDOT Houston district is highly recommended to mitigate the effects of the off tracking of heavy vehicles.

2) Although the current dowel bar location of the new U-turn curb design is found to be structurally adequate, it is recommended to change the location of the curb dowel to be further from the traffic face of a CCCG system for better performance. A distance between the location of dowel and the traffic face of CCCG of 8 in. or higher is recommended.

3) Curb width of 24 in. or higher is recommended to provide adequate structural capacity.

4) It is also recommended to use an epoxy-grouted curb dowel instead of a manually inserted straight dowel bar to ensure better bond performance between dowel bar and concrete in a CCCG system.

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# Appendix: Improved Design Standards for Curb and Gutter

**1. Area without off tracking loads**

Research findings from this study did not identify any reasons to modify the current Roadway Standard Plan for the concrete curb and curb and gutter (CCCG-01).

**2. Area under off tracking loads**

Based on the research efforts in this study, the following recommendations are proposed for the new construction of CCCG systems for the areas experiencing off tracking load conditions.

- The use of the new U-turn curb design from the TxDOT Houston district is highly recommended for areas affected by the off tracking of heavy vehicles.
- Although the current dowel bar location of the new U-turn curb design is found to be structurally adequate, it is recommended to change the location of curb dowel to the further location from the traffic face of a CCCG system for better performance. A distance between the location of dowel and the traffic face of CCCG of 8 in. or higher is recommended.
- Curb width of 24 in. or higher is recommended to provide adequate structural capacity.
- It is also recommended to use an epoxy-grouted curb dowel instead of a manually inserted straight dowel bar to ensure better bond performance between the dowel bar and the concrete in a CCCG system.