This study addressed the design and performance of longitudinal barriers for construction zones. The strengths of various connections for portable concrete median barriers (PCB) are analyzed and theoretical treatments of behavior of the PCB during a collision are presented. These analyses along with cost data and crash test information are used to develop a barrier performance rating and selection system. Crash tests on a non-deflecting PCB with various types and sizes of vehicles are reported.

This report consists of three volumes:

Volume 1: Summary Report
Volume 2: Appendix A - Documentation of Crash Tests
Volume 3: Appendices B, C, D, E and F - Theoretical and Economic Analyses
# Metric Conversion Factors

## Approximate Conversions from Metric Measures

### Length

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BARRIERS IN CONSTRUCTION ZONES

APPENDIX B

Simplified Energy Analysis

Prepared for
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by
Don L. Ivey
Research Engineer
Texas A&M Research Foundation
Texas Transportation Institute
The Texas A&M University System
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Energy Analysis of CMB

A portable CMB subjected to a vehicle impact at or near one of the joints between segments can be analyzed using the energy method. The analysis is subject to a number of simplifying assumptions. The positions of barrier segments before and after vehicle impact are shown in Figure 1 from an overhead view.

The major simplifying assumptions are:

- Only two segments of the barrier move.
- The amount of vehicle kinetic energy associated with the lateral component of vehicle velocity is expended in work on the barrier and the vehicle.
- The complex development of moment in a barrier joint can be approximated as shown in Figure 2.
- Static and sliding friction between the barrier base and the support media can be approximated as shown by Figure 3.
- The work done in deforming vehicle structure can be approximated by the equation derived from Figure 4.

The basic energy balance equation to be used is

\[ E_{d} = E_{m} + E_{w} + E_{c} \]  \hspace{1cm} (1)

where

- \( E_{d} \) = that amount of kinetic energy associated with the lateral component of vehicle velocity, kip-ft.
- \( E_{m} \) = the total of \( Em_1 \), \( Em_2 \), and \( Em_3 \), the total work done in rotating barrier joints, kip-ft.
- \( E_{w} \) = the amount of vehicle kinetic energy associated with the lateral component of vehicle velocity.
- \( E_{c} \) = represents the change in vehicle kinetic energy due to the impact period between first contact and the time when the vehicle is parallel to the barrier.
Joint No. 1 L 2 L 3

11(a) Before impact

Vehicle exit velocity vector

Vehicle entry velocity vector, \( V, \text{mph} \)

11(b) After impact

Vehicle entry trajectory

\( \Delta \) - Lateral deflection of joint 2
\( \phi \) - Angular rotation of segments 12 and 23
\( M_\phi \) - Moment developed in joints 1, 2, and 3 (see Figure 2)

Definition of Terms:

L - Barrier segment length
\( \Delta \) - Lateral deflection of joint 2
\( \phi \) - Angular rotation of segments 12 and 23
\( M_\phi \) - Moment developed in joints 1, 2, and 3 (see Figure 2)

Figure 1. Idealized barrier segment positions before and after impact.
Figure 2. Joint moment as a function of rotation.

Figure 3. Barrier-support media friction as a function of barrier segment rotation, \( \phi \).
Kinetic energy due to lateral velocity component, $E_z$

$$E_z = \frac{1}{2} W \left( \frac{V}{g} \right)^2, \text{kip-ft}$$

Note:

$$E_{c\Delta=0} = \frac{A_1}{B_1} E_z$$

$$E_{c\Delta=\Delta_{\text{max}}} = \frac{A_2}{B_1} E_z$$

$$E_{c\Delta} = \frac{A_{\Delta}}{B_1} E_z \quad (1)$$

Now $A_{\Delta}$ can be proportioned from $A_2$ to $A_1$ for different levels of deflection by the equation

$$A_{\Delta} = A_1 - (A_1 - A_2) \frac{\Delta}{\Delta_{\text{max}}} \quad (2)$$

and

$$\Delta = L \sin \theta \quad (3)$$

By substituting $A_{\Delta}$ and $\Delta$ into equation (1) we find

$$E_c = \frac{(A_1 - A_2)}{\Delta_{\text{max}}} L \sin \phi \frac{E_z}{B_1}$$

Figure 4. Illustration of estimating work done in deforming vehicle structure.
\[ E_{\mu} = \text{the work done in sliding two barrier segments through the angle } \phi, \text{ kip-ft.} \]

\[ E_{c} = \text{the work done in deforming the vehicle structure during impact, kip-ft. (See Figure 4)} \]

Note, \( E_{m} = E_{m1} + E_{m2} + E_{m3} \) \hspace{1cm} (2)

where

\[ E_{m1} = \text{the work done in rotating joint 1 through the angle } \phi, \text{ kip-ft. (See Figure 2)} \]

\[ E_{m2} = \text{the work done in rotating joint 2 through the angle } 2\phi, \text{ kip-ft. (See Figure 2)} \]

\[ E_{m3} = \text{the work done in rotating joint 3 through the angle } \phi, \text{ kip-ft. (See Figure 2)} \]

The values of \( E_{m1} \) and \( E_{m3} \) can be determined from the following integrals (or numerically from Figure 2).

\[ E_{m1} = \int_{0}^{\phi} M d\phi, \quad E_{m2} = \int_{0}^{2\phi} M d\phi, \quad E_{m3} = \int_{0}^{\phi} M d\phi \] \hspace{1cm} (3)

From Figure 1 it is seen that joints 1 and 3 go through an angular deformation of \( \phi \) while joint 2 goes through \( 2\phi \).

\[ \phi = \text{the maximum rotation due to impact of segment 1-2 and 2-3.} \]

\[ M = \text{the moment developed by a joint when subjected to an angular deformation of } \phi. \]

The work done in sliding the barrier segments can be computed by multiplying barrier segment weight by the amount of friction developed in any interval of sliding movement and summing all these differential portions of work. This value is approximated by Equation 4, which can be solved numerically by referring to Figure 3.

\[ E_{\mu} = W_{i} L^{2} \int_{0}^{\phi} \mu d\phi \] \hspace{1cm} (4)

where

\[ W_{i} = \text{the weight per unit length of the barrier, kip-ft.} \]

\[ \mu = \text{the coefficient of friction associated with any movement of the barrier (See Figure 3), dimensionless.} \]
The length of a barrier segment, ft.

The work done in deforming the automobile structure, $E_c$, is approximated by Equation 5.

$$E_c = \frac{E_x}{B_1} \left( A_1 - \frac{(A_1 - A_2) L \sin \phi}{\Delta \text{max}} \right)$$

where

$A_1$ = constant used in determining $E_c$, kip-ft. (See Figure 4)

$A_2$ = constant used in determining $E_c$, kip-ft. (See Figure 4)

$B_1$ = constant used in determining $E_c$, kip-ft. (See Figure 4)

$\Delta \text{max}$ = maximum functional barrier deflection, ft. (This is simply the maximum deflection that can be produced and the barrier still be considered to be geometrically continuous. It is taken to be five feet.

$W_i$ = weight per unit length of barrier, kip-ft

$L$ = barrier segment length, ft.

$\phi$ = the angular movement of one of the two moving barrier segments, radians.

By substituting the values of $E_{mt}$, $E_u$ and $E_c$ into Equation 1 the following equation results:

$$E_x = 2 \int_0^{\phi} M \, d\phi + \int_0^{2\phi} M \, d\phi + W_1 \frac{L^2}{\Delta \text{max}} \int_0^{\phi} \mu \, d\phi$$

$$1 - \frac{1}{B_1} \left( A_1 - \frac{(A_1 - A_2) L \sin \phi}{\Delta \text{max}} \right)$$

The control value of $E_x$ is calculated from the equation

$$E_x = \frac{1}{2} \frac{W}{g} (v \sin \phi)^2$$

where

$W$ = vehicle weight, kips

$g$ = acceleration of gravity, ft/sec$^2$

$v$ = vehicle velocity, ft/sec
and $\theta = \text{vehicle impact angle, degrees}$

The solution of Equation 6 can be quickly achieved by the method of finite differences; assuming a value of $\phi$, calculating the value of the right side of the equation and comparing the calculated value with the known value of $E_\theta$ from Equation 7 as shown in Figure 5. If $E_\theta$ from Equation 6 is greater than $E_\theta$ from Equation 7 the value of $\phi$ is too large. Therefore, a smaller value should be estimated and the procedure repeated. If $E_\theta$ (Eq. 6) is less than $E_\theta$ (Eq. 7) the value of $\phi$ is too small and a larger value should be chosen for the next trial. The correct value of $\phi$ (i.e. the one necessary to balance the equation) will be defined within 1% accuracy within ten iterations if a reasonable first estimate of $\phi$ is chosen.
Assume \( \pi \). Calculate \( \int_0^{\phi} M d\phi \) (Fig. 2)

Calculate \( \int_0^{2\phi} M d\phi \) (Fig. 2)

Calculate \( E_\pi \) from Eq. 6 (Fig. 6)

Calculate \( C = \frac{E_\pi}{E_{l7}} \)

If \( C > 1.01 \) or \( C \leq 0.99 \), then \( \phi_{i+1} = C \phi_i \)

Output \( \phi, \Delta, E_m, E_u, E_c \) & \( E_\pi \)

STOP

Figure 5. Flow diagram to solve Equation 6.
\( \mu_i \) - Friction coefficient for segment \( i \)
\( \rho_i \) - Distance from reference end to center of mass for segment \( i \)
\( \phi_e \) - End of elastic deformation in joint spring
\( \phi_f \) - Failure deformation in spring
\( \phi_i \) - Rotation of segment \( i \)
\( \dot{\phi}_i \) - Rotational velocity of segment \( i \)
\( \phi_p \) - End of plastic range for deformation in joint spring
\( \phi_s \) - Rotational slack in joint spring
\( \omega_i \) - Rotational velocity of segment \( i \)
BARRIERS IN CONSTRUCTION ZONES

APPENDIX C

Documentation of Concrete Median Barrier
Advanced Dynamic Analysis

Prepared for
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Office of Research
Federal Highway Administration
U. S. Department of Transportation

by
Kenneth C. Walker
Research Assistant

and
H. E. Ross, Jr.
Research Engineer

Texas A&M Research Foundation
Texas Transportation Institute
The Texas A&M University System
April 1985
DEVELOPMENT OF SIMULATION PROGRAM

System Characterization

A free-standing, segmental concrete median barrier (CMS) system can be modeled as a series of "n" articulated rigid segments. The geometry is defined in the global coordinate system with the X' and Y' axes. The i-th segment has its own local coordinate system given by the X_i and Y_i axes. Each link is characterized by four variables: length, L_i; distance from reference end to the center of mass, p_i; mass of segment, M_i; and friction coefficient with the roadway, μ_i. The spatial relationship is defined by the generalized coordinates given in the global system. These are: the distance from the global origin to the reference end of segment 1, X'_1, Y'_1, and the global rotational angle of each segment, φ_1 to φ_n. This gives n+2 degrees of freedom. The idealized model is shown in Figure 6.

Segment Center of Mass Location

The relationship between segment fixed coordinates (X_i,Y_i) and space-fixed coordinates (X',Y') is given as:

\[ X' = X_i \cos \phi_i - Y_i \sin \phi_i \]  
\[ Y' = X_i \sin \phi_i + Y_i \cos \phi_i \]

The equivalent matrix form is

\[
\begin{bmatrix} X' \\ Y' \end{bmatrix} = \begin{bmatrix} T_i^T \end{bmatrix} \begin{bmatrix} X_i \\ Y_i \end{bmatrix}
\]

where

\[
T_i^T = \begin{bmatrix} \cos \phi_i & -\sin \phi_i \\ \sin \phi_i & \cos \phi_i \end{bmatrix}
\]
Figure 6. Idealized Model of CMB System.
It can be shown that the transformation matrix \([T]\) is an orthogonal matrix in which its inverse is identical to its transpose, and matrix multiplication of the two, \([T^i][T^i]^T = [I]\) is the identity matrix. Solving for the segment-fixed coordinates in terms of the space-fixed coordinates,

\[
\begin{bmatrix}
X_1 \\
Y_1
\end{bmatrix} = \begin{bmatrix}
T_1
\end{bmatrix}^T \begin{bmatrix}
X' \\
Y'
\end{bmatrix} \ldots \ldots \ldots \ldots \ldots (12)
\]

The position of the center of mass of segment can be defined as

\[
\begin{bmatrix}
X_1 \\
Y_1
\end{bmatrix} = \begin{bmatrix}
X_R \\
Y_R
\end{bmatrix} + \begin{bmatrix}
T_1
\end{bmatrix} \begin{bmatrix}
\rho_1 \\
0
\end{bmatrix} \ldots \ldots \ldots \ldots \ldots (13)
\]

The position of segment 2 can be written as

\[
\begin{bmatrix}
X_2 \\
Y_2
\end{bmatrix} = \begin{bmatrix}
X_R \\
Y_R
\end{bmatrix} + \begin{bmatrix}
T_1
\end{bmatrix} \begin{bmatrix}
L_1 \\
0
\end{bmatrix} + \begin{bmatrix}
T_2
\end{bmatrix} \begin{bmatrix}
\rho_2 \\
0
\end{bmatrix} \ldots \ldots \ldots \ldots \ldots (14)
\]

This can be generalized for any segment "i" (except for i=1) as

\[
\begin{bmatrix}
X_i \\
Y_i
\end{bmatrix} = \begin{bmatrix}
X_R \\
Y_R
\end{bmatrix} + \sum_{j=1}^{i-1} \begin{bmatrix}
T_j
\end{bmatrix} \begin{bmatrix}
L_j \\
0
\end{bmatrix} + \begin{bmatrix}
T_i
\end{bmatrix} \begin{bmatrix}
\rho_i \\
0
\end{bmatrix} \ldots \ldots \ldots \ldots \ldots (15)
\]

or in an expanded form

\[
X_i = X_R + \sum_{j=1}^{i-1} T_{i1}^j L_j + T_{i1} \rho_i \ldots \ldots \ldots \ldots \ldots \ldots (16)
\]

\[
Y_i = Y_R + \sum_{j=1}^{i-1} T_{i1}^j L_j + T_{i2} \rho_i \ldots \ldots \ldots \ldots \ldots \ldots (17)
\]
where \( T_{11}^i = \cos \phi_i \) and \( T_{21}^i = \sin \phi_i \).

**Segment Center of Mass Velocity**

To get the global velocities of each center of mass, the time derivative of each term must be taken. For the first segment this gives

\[
\dot{x}_1 = \dot{x}_1^{12} + \frac{\partial T_{11}^1}{\partial \phi_1} \dot{\phi}_1 \rho_1 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (18)
\]

\[
\dot{y}_1 = \dot{y}_1^{12} + \frac{\partial T_{21}^1}{\partial \phi_1} \dot{\phi}_1 \rho_1 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (19)
\]

The velocity of the \( i \)-th segment of the remaining "n-1" segments is given by:

\[
\dot{x}_i = \dot{x}_R + \sum_{j=1}^{i-1} \frac{\partial T_{11}^j}{\partial \phi_j} \dot{\phi}_j L_j + \frac{\partial T_{11}^i}{\partial \phi_i} \dot{\phi}_i \rho_i \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (20)
\]

\[
\dot{y}_i = \dot{y}_R + \sum_{j=1}^{i-1} \frac{\partial T_{21}^j}{\partial \phi_j} \dot{\phi}_j L_j + \frac{\partial T_{21}^i}{\partial \phi_i} \dot{\phi}_i \rho_i \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (21)
\]

and the squared terms are

\[
\left[ \dot{x}_i \right]^2 = \left[ \dot{x}_R + \sum_{j=1}^{i-1} \frac{\partial T_{11}^j}{\partial \phi_j} \dot{\phi}_j L_j + \frac{\partial T_{11}^i}{\partial \phi_i} \dot{\phi}_i \rho_i \right]^2 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (22)
\]

\[
\left[ \dot{y}_i \right]^2 = \left[ \dot{y}_R + \sum_{j=1}^{i-1} \frac{\partial T_{21}^j}{\partial \phi_j} \dot{\phi}_j L_j + \frac{\partial T_{21}^i}{\partial \phi_i} \dot{\phi}_i \rho_i \right]^2 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (23)
\]
Segment Angular Velocities

The angular velocity of segment "i" ($\omega_i$) is expressed as the time derivative of that segment's rotational displacement ($\phi_i$). Therefore

$$\omega_i = \dot{\phi}_i$$

and

$$(\omega_i)^2 = (\dot{\phi}_i)^2$$

LaGrange's Equation

The motion of this system of discrete masses can be described by LaGrange's equation. It is given as

$$\frac{\partial U}{\partial q_k} - \frac{\partial U}{\partial q_k} + \frac{\partial V}{\partial q_k} = Q_k$$

where $t = \text{time}$, $U = \text{kinetic energy of the system}$, $V = \text{potential energy of the system}$; $q_k = \text{generalized coordinate}$, $\dot{q}_k = \text{generalized velocity}$, $Q_k = \text{generalized forces acting on the system not derivable from potential functions}$, and $k = 1, 1 \ldots n+2$, for the generalized problem.

The generalized force on the right-hand side can be defined as

$$Q_k = Q_{e_k} + Q_{f_k}$$

in which $Q_{e_k} = \text{generalized force from externally applied loads (vehicle loads)}$, and $Q_{f_k} = \text{generalized force due to the Coulomb damping friction force at barrier-roadway interface}$.

In this problem, the potential energy of the system, $V$, is derived from the spring forces (actually end moments) due to relative rotations.
between two segments. The potential energy due to position is assumed to be zero. For convenience let

\[ F_{s_k} = -\frac{\partial W}{\partial q_k} \quad \ldots \ldots \ldots \ldots \quad (28) \]

where \( F_{s_k} \) = generalized force due to strain energy.

By substituting Eqs. 27 and 28 into Eq. 26 and rearranging gives:

\[ \frac{\partial U}{\partial q_k} - \frac{\partial U}{\partial q_k} = F_{s_k} + Q_{ek} + Q_{fk} \quad \ldots \ldots \ldots \ldots \quad (29) \]

If there are "n" segments, there will be a set of "n+2" second order, coupled nonlinear differential equations. For convenience, the above equation can be written in matrix form as follows:

\[ [D] \{ \ddot{q} \} = \{ \dot{E} \} + \{ F_s \} + \{ Q_e \} + \{ Q_f \} \quad \ldots \ldots \ldots \quad (30) \]

Matrix \([D]\) contains all of the coefficients of the generalized accelerations and \( \{ \dot{E} \} \) is a column vector containing the negative of all remaining terms from the left-hand side of Eq. 29.

**Contributions of Kinetic Energy to Equations of Motion**

The kinetic energy of a system of "n" particles is given by:

\[ U = \frac{1}{2} \sum_{i=1}^{n} M_i \left[ \dot{X}_i^2 + \dot{Y}_i^2 \right] + \frac{1}{2} \sum_{i=1}^{n} I_i \omega_i^2 \quad \ldots \ldots \quad (31) \]

where \( M_i \) = mass of segment \( i \); \( I_i \) = mass moment of inertia of segment \( i \) about the \( Z_i \) axis; \( (\dot{X}_i)^2 \) = square of \( i \)-th segment translational velocity in \( X' \) direction; \( (\dot{Y}_i)^2 \) = square of \( i \)-th segment translational velocity
n Y' direction; and \( \omega_i^2 \) = square of \( i \)-th segment rotational velocity.

Equations 22 and 23 define \((x_i')^2\) and \((y_i')^2\) and Eq. 25 gives the value of \((\omega_i)^2\). These expressions can be substituted into Eq. 26 to give the general formula for the total kinetic energy of the system. The result is

\[
U = \frac{1}{2} \sum_{i=1}^{n} M_i \left\{ \left( \dot{x}_i' + \sum_{j=1}^{i-1} \frac{\partial T_{ij}}{\partial \dot{\phi}_j} \phi_j \dot{L}_j + \frac{\partial T_{ii}}{\partial \phi_i} \phi_i \rho_i \right)^2 + \left( \dot{y}_i' + \sum_{j=1}^{i-1} \frac{\partial T_{21}}{\partial \dot{\phi}_j} \phi_j \dot{L}_j + \frac{\partial T_{21}}{\partial \phi_i} \phi_i \rho_i \right)^2 + \frac{1}{2} \sum_{i=1}^{n} I_i \left( \ddot{\phi}_i \right)^2 \right\} \tag{32}
\]

By taking the derivative of this equation first with respect to each of the generalized velocities and then with respect to time, a set of "n+2" equations with functions of the generalized displacements, velocities, and accelerations will be generated. After separating the terms that include a generalized acceleration and factoring out the coefficients, a set of equations to calculate the [D] matrix will remain. The results of this expansion is summarized in EQUATIONS OF MOTION.

Next, the derivative of the kinetic energy expression with respect to the generalized displacements is taken. These terms are then added to the remaining terms from the previous step. After reversing each of their algebraic signs, there are the "n+2" equations that make up the
Contributions of Potential Energy
to Equations of Motion

Each joint of this model is designed to have five regions of spring response. The first region is a slack region in which there is no moment developed due to spring deformation. There is no energy associated with this deflection. In the second range, the moment generated is proportional to the relative rotation minus some value of maximum slack rotation. This stored energy is completely recoverable by the spring. A plastic region of deformation is next, where there is little or no increase in joint moment due to additional deformation of the spring. Only a small amount of this energy can be returned to the system in elastic rebound of the spring. The fourth characteristic zone is one of lock-up, where a large increase in joint moment occurs with a very small increase in differential rotation. None of this energy can be regained. The final region is one of spring failure, in which the moment capacity falls to and remains at zero. Once this occurs all stored energy is lost. The relationship of each of these characteristic regions is shown in Figure 7.

At each joint the differential rotation will be the difference in angular rotation between segment "i" and segment "i+1".

\[ \Delta \phi_i = \phi_{i+1} - \phi_i \]  

(33)

The potential energy of any one spring is defined as

\[ V_i = \int_0^{\Delta \phi} M u(\Delta \phi) d(\Delta \phi) \]  

(34)
NOTE: Dashed lines show unloading direction for plastic and lockup ranges.

Figure 7. Joint Spring Moment-Differential Rotation Relationship.
which can be expanded using the relationship of Eq. 33.

\[ V_i = \int_0^{\phi_i + 1} \mu \Delta \phi_i \, d(\phi_i + 1) - \int_0^{\phi_i} \mu \Delta \phi_i \, d\phi_i \quad \ldots \ldots \quad (35) \]

If the individual contributions are summed over the "n-1" possible springs, the total potential energy can be expressed as:

\[ V = \sum_{i=1}^{n-1} \left[ \int_0^{\phi_i + 1} \mu \Delta \phi_i \, d(\phi_i + 1) - \int_0^{\phi_i} \mu \Delta \phi_i \, d\phi_i \right] \quad \ldots \ldots \quad (36) \]

The contribution of this potential energy to the equations of motion is found by taking the derivative with respect to each of the generalized coordinates. However, the potential energy is independent of the \( X_r \) and \( Y_r \) coordinates, so the necessary derivatives must only be taken with respect to each rotation, \( \phi_i \). When this is done, the \( \{F_s\} \) vector will be the negative of these terms, where \( F_s \) is the resultant from differentiating with respect to \( q_k \) or \( \phi_{k-2} \). The equations for the \( \{F_s\} \) vector are contained in EQUATIONS OF MOTION.

**Generalized Forces due to External Loads**

The external load in this model consists of an impact force in the global \( Y' \) direction that is input with a given magnitude, location, and time of application. A second force in the global \( X' \) direction is defined as an input fractional amount of the original force. The first force is defined as \( F_Y \), where

\[ F_Y = F_Y(X_F, t) \quad \ldots \ldots \ldots \ldots \quad (37) \]

and the second force is \( F_{X'} \), where
Before these forces can be included in the equations of motion, their contribution to each of the generalized coordinates must be determined. The principle of virtual work will be used.

**Location of Force**

To find the work of these forces, the segment on which the load is applied must be determined, and its rotation must be established. This is shown in Figure 8. This is found when a segment's end point satisfies the relation

$$x_i' \leq x_F > x_i^t$$  \hspace{1cm} (39)

where $i$ is the number of the segment the force acts on. The initial end of segment $i$ is at

$$V_i^t = x_i^r + T_{11}^1 L_1 + T_{11}^2 L_2 + \cdots + T_{11}^{i-1} L_{i-1}$$  \hspace{1cm} (40)

and the final end is at

$$x_i^t = x_i^r + T_{11}^i L_i$$  \hspace{1cm} (41)

**Virtual Work of External Loads**

The virtual work of the external loads is given by

$$\delta W = F_x' \delta x_{Ai} + F_y' \delta y_{Ai}$$  \hspace{1cm} (42)

Expressed in terms of generalized coordinates and forces, this virtual work is
Figure 8. Location of Vehicle Impact Force Along Barrier.
\[ \delta W = \sum_{k=1}^{n+2} (q_{ek} \delta q_k) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (43) \]

where \( n+2 \) = number of degrees of freedom (\( n \) = number of barrier segments).

To transform Equation 42 into an expression with generalized coordinates, use the relation

\[ X_{Ai}^i = X_{iR}^i + T_{11}^i (\rho_i + r_{XA_i}) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (44) \]

where \( X_{iR}^i \) was defined above and

\[ r_{XA_i} = \frac{X_F^i - X_{iR}^i}{\cos \phi_i} - \rho_i \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (45) \]

The impact location in the \( Y' \) direction is given by

\[ Y_{Ai}^i = Y_{iR}^i + T_{21}^i (\rho_i + r_{XA_i}) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (46) \]

where

\[ Y_{iR}^i = Y_R^i + T_{21}^i L_1 + T_{21}^2 L_2 + \ldots + T_{21}^{i-1} L_{i-1} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (47) \]

Thus, the point of application of force is

\[ X_{Ai}^i = X_{iR}^i + T_{11}^i \left( \frac{X_F^i - X_{iR}^i}{\cos \phi_i} \right) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (48) \]

But \( T_{11}^i = \cos \phi_i \), so that

\[ X_{Ai}^i = X_F^i \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (49) \]

In the same manner,

\[ Y_{Ai}^i = Y_{iR}^i + T_{21}^i \frac{X_F^i - X_{iR}^i}{\cos \phi_i} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (50) \]
and since \( T_{2i} = \sin \phi_i \)

\[
Y_A^i = Y_{iR}^i + \tan \phi_i (X_{iF}^i - X_{iR}^i) \quad \cdots \cdots \cdots \quad (51)
\]

With expressions for \( X_{Ai}^i \) and \( Y_{Ai}^i \) defined, the first differential is given as

\[
\delta X_{Ai}^i = \sum_{k=1}^{n+2} \frac{\partial X_{Ai}^i}{\partial q_k} \delta q_k \quad \cdots \cdots \cdots \quad (52)
\]

and

\[
\delta Y_{Ai}^i = \sum_{k=1}^{n+2} \frac{\partial Y_{Ai}^i}{\partial q_k} \delta q_k \quad \cdots \cdots \cdots \quad (53)
\]

These expressions can be substituted into Equation 42 to get

\[
\delta W = F_X^i \sum_{k=1}^{n+2} \frac{\partial X_{Ai}^i}{\partial q_k} \delta q_k + F_Y^i \sum_{k=1}^{n+2} \frac{\partial Y_{Ai}^i}{\partial q_k} \delta q_k \quad \cdots \cdots \quad (54)
\]

Rearranging terms gives

\[
\delta W = \sum_{k=1}^{n+2} \left[ F_X^i \frac{\partial X_{Ai}^i}{\partial q_k} + F_Y^i \frac{\partial Y_{Ai}^i}{\partial q_k} \right] \delta q_k
\]

If this is compared to Equation 43 the generalized force is found to be

\[
Q_{ek} = F_X^i \frac{\partial X_{Ai}^i}{\partial q_k} + F_Y^i \frac{\partial Y_{Ai}^i}{\partial q_k} \quad \cdots \cdots \cdots \quad (55)
\]
Equation 55 with \( k = 1, 2, \ldots, n+2 \) defines the term in row \( k \) for the column vector \( \{Q_e\} \) in Equation 30. The expanded form for each row of \( \{Q_e\} \) is given in EQUATIONS OF MOTION.

**Generalized Forces due to Friction**

**at the Roadway-Barrier Interface**

The friction force developed at the road-barrier interface can be broken up into two components. The first part is due to translation of the barrier segment, and the second part is due to rotation of that segment. The generalized forces for translation will be found first, and then those for rotation.

**Translation Friction Force**

The velocity of the \( i \)-th segment in the fixed \( X \)-axis and \( Y \)-axis directions was found previously in Equations 20 and 21. Since both expressions for the center of mass location are functions of the generalized coordinates, it can be shown that

\[
\dot{X}_i = \sum_{k=1}^{n+2} \frac{\partial X_i}{\partial q_k} \dot{q}_k = \sum_{k=1}^{n+2} \frac{\partial X_i}{\partial q_k} \ddot{q}_k \quad \ldots \quad (56)
\]

and in a like manner

\[
\dot{Y}_i = \sum_{k=1}^{n+2} \frac{\partial Y_i}{\partial q_k} \dot{q}_k \quad \ldots \quad (57)
\]

Define the net translational velocity to be

\[
\dot{R}_i = \left[ (\dot{X}_i)^2 + (\dot{Y}_i)^2 \right]^{1/2} \quad \ldots \quad (58)
\]
and the maximum resultant friction force on segment $i$ as

$$R_{F_i} = (W_i)(\mu_i)$$  \hspace{1cm} (59)$$

where $W_i =$ weight of segment $i$ and $\mu_i =$ coefficient of friction between roadway and barrier.

Now, expressions to find the component of force that oppose the barrier's translational motion in each fixed axis direction are found to be

$$F_{fx_i} = -\left( \frac{x_i}{R_i} \right) R_{F_i}$$  \hspace{1cm} (60)$$

and

$$F_{fy_i} = -\left( \frac{y_i}{R_i} \right) R_{F_i}$$  \hspace{1cm} (61)$$

To help avoid the numerical instabilities that occur when $x_i$ or $y_i$ change sign, an adjustment in the frictional forces will be made. For values of segment velocity less than a very small value, $\dot{\varepsilon}_T$, the force will be reduced according to the equation.

$$R_{F_i} = C_t R_{F_i}$$  \hspace{1cm} (62)$$

The relationship of reduction constant to translational velocity is given by

$$C_t = \begin{cases} \sin \frac{\pi}{2} \frac{\dot{R}_i}{\dot{\varepsilon}_T} & \text{For } \dot{R}_i < \dot{\varepsilon}_T \\ 1.0 & \text{For } \dot{R}_i \geq \dot{\varepsilon}_T \end{cases} \hspace{1cm} (63)$$

$$C_t = \begin{cases} \sin \frac{\pi}{2} \frac{\dot{R}_i}{\dot{\varepsilon}_T} & \text{For } \dot{R}_i < \dot{\varepsilon}_T \\ 1.0 & \text{For } \dot{R}_i \geq \dot{\varepsilon}_T \end{cases} \hspace{1cm} (64)$$

Figure 9 shows the $C_t - \dot{R}_i$ curve for making this adjustment.
For $\dot{R}_i < \dot{e}_T$

$$C_T = \sin \left( \frac{\pi}{2} \frac{\dot{R}_i}{\dot{e}_T} \right)$$

Figure 9. Adjustment Coefficient for Translational Friction Force.
Rotational Friction Force

The contribution of the rotational friction component can be found by examining the distribution of friction forces as shown in Figure 10. The moment due to the friction force can be calculated as

\[ M_{f_i} = -\frac{\dot{\phi}_i \ W_i \mu_i \ L_i}{4 |\dot{\phi}_i|} \quad \cdots \cdots \cdots \cdots \quad (65) \]

Again, to compensate for possible numerical instability when the rotational velocity becomes very small or changes sign, an adjustment factor of

\[ C_r = \sin \left( \frac{\pi}{2} \frac{\dot{\phi}_i}{\dot{\varepsilon}_R} \right) \quad \text{For } \dot{\phi}_i \leq \dot{\varepsilon}_R \quad \cdots \cdots \cdots \quad (66) \]

will be applied to the frictional moment as given here

\[ M_{f_i} = C_r M_{f_i} \quad \cdots \cdots \cdots \cdots \quad (67) \]

Virtual Work of Friction Forces

The virtual work done by the translation friction force is given by

\[ \delta W_{F_X} = \sum_{i=1}^{n} (F_{fX_i} \delta X_i + F_{fY_i} \delta Y_i) \quad \cdots \cdots \cdots \cdots \quad (68) \]

In a like manner the virtual work done by the generalized friction forces can be given as

\[ \delta W_f = \sum_{k=1}^{n+2} (Q_{fk}) \delta q_k \quad \cdots \cdots \cdots \cdots \quad (69) \]
Figure 10. Distribution of Friction Force due to Rotation of Segment i.
The expressions for \( X_i \) and \( Y_i \) are given in Equations 22 and 23, hence

\[
X_i = \sum_{i=1}^{n+2} \frac{\partial X_i}{\partial q_k} \delta q_k \tag{70}
\]

\[
Y_i = \sum_{i=1}^{n+2} \frac{\partial Y_i}{\partial q_k} \delta q_k \tag{71}
\]

By substituting these two expressions into Equation 68,

\[
\delta W_{ft} = \sum_{i=1}^{n} \sum_{k=1}^{n} \left[ F_{X_i} \frac{\partial X_i}{\partial q_k} + F_{Y_i} \frac{\partial Y_i}{\partial q_k} \right] \delta q_k \tag{72}
\]

If Equations 69 and 72 are compared it can be shown that the generalized friction force due to translational movement is

\[
Q_{ftk} = \sum_{i=1}^{n} \left[ F_{X_i} \frac{\partial X_i}{\partial q_k} + F_{Y_i} \frac{\partial Y_i}{\partial q_k} \right] \tag{73}
\]

In the same way, the generalized rotational friction force can be found. The virtual work of the rotational forces is

\[
\delta W_{fr} = \sum_{i=1}^{n} M_i \phi_i \tag{74}
\]

and the virtual work of the generalized rotational friction force is

\[
\delta W_f = \sum_{k+1}^{n+2} Q_{frk} \delta q_k \tag{75}
\]
Since each of the segment rotational angles $\phi_i$ correspond to the generalized coordinate $q_{i+2}$, the generalized force due to rotational friction is

$$Q_{frk} = M_f(k-2) \quad \ldots \ldots . \ldots \ldots (76)$$

where $M_f(k-2)$ is defined in Equation 65 or 67. The total generalized friction force is given by

$$Q_{fk} = Q_{ftk} + Q_{frk} \quad \ldots \ldots . \ldots \ldots (77)$$

The expansion of this expression is given in EQUATIONS OF MOTION.

**Solution of Equations**

**The Runge-Kutta Method**

The matrix equations of motion for the barrier system as given in Equation 11 are of the form in which the second derivative, $\ddot{q}_k$, ($k=1, \ldots, n$), can be expressed as a function of the first derivative, $\dot{q}_k$, the dependent variable, $\dot{q}_k$, and the independent variable, $t$(time). Therefore the equations were solved using the Runge-Kutta method for ordinary differential equations (1).

The right-hand side of Equation 11 can be redefined as

$$\{R\} = \{E\} + \{F_s\} + \{Q_e\} + \{Q_f\} \quad \ldots \ldots . \ldots \ldots (78)$$

Using the inverse of the $[D]$ matrix to find an expression for the generalized accelerations

$$\{\ddot{q}\} = [D]^{-1}\{R\} \quad \ldots \ldots . \ldots \ldots (79)$$
The \([D]^{-1}\) matrix is a function of displacements only, but the \(\{R\}\) column vector is dependent on both displacements and velocities. This will be noted as

\[
[D]^{-1} = [D (\{q\})]^{-1}
\]  
(80)

and

\[
\{R\} = \{R(\{q\}, \{\dot{q}\})\}
\]  
(81)

so that

\[
\{\ddot{q}\} = [D(\{q\})]^{-1} \{R(\{q\}, \{\dot{q}\})\}
\]  
(82)

Solution of Equation 82 was done with a stepwise increment of time, \(\Delta t\), using the equations given below.

\[
\{AY_1\} = \Delta t \cdot \{\dot{q}\}
\]  
(83)

\[
\{AZ_1\} = \Delta t \cdot [D(\{q\})]^{-1} \{R(\{q\}, \{\dot{q}\})\}
\]  
(84)

\[
\{AY_2\} = \Delta t \cdot \{\dot{q}\} + \frac{1}{2} \Delta t \{AZ_1\}
\]  
(85)

\[
\{AZ_2\} = \Delta t \cdot [D(\{q\} + \frac{1}{2} \{AY_1\})]^{-1} \{R(\{q\} + \frac{1}{2} \{AY_1\}, \{\dot{q}\})
\]

\[
+ \frac{1}{2} \{AZ_1\}\}
\]  
(86)

\[
\{AY_3\} = \Delta t \cdot \{\dot{q}\} + \frac{1}{2} \Delta t \cdot \{AZ_2\}
\]  
(87)

\[
\{AZ_3\} = \Delta t \cdot [D(\{q\} + \frac{1}{2} \{AY_2\})]^{-1} \{R(\{q\} + \frac{1}{2} \{AY_2\}, \{\dot{q}\})
\]

\[
+ \frac{1}{2} \{AZ_2\}\}
\]  
(88)

\[
\{AY_4\} = \Delta t \cdot \{\dot{q}\} + t \cdot \{AZ_3\}
\]  
(89)
\[ \{AZ_4\} = t \cdot \left[D\{q\} + \{AY_3\}\right]^{-1}R\{\{q\} + \{AY_3\}, \{q\} + \{AZ_3\}\} \quad (90) \]

\[ \{AY\} = \frac{1}{6} \cdot \left\{\{AY_1\} + 2\{AY_2\} + 2\{AY_3\} + \{AY_4\}\right\} \quad \ldots \ldots \quad (91) \]

\[ \{AZ\} = \frac{1}{6} \cdot \left\{\{AZ_1\} + 2\{AZ_2\} + 2\{AY_3\} + \{AY_4\}\right\} \quad \ldots \ldots \quad (92) \]

The new values of time, displacement, and velocity at time \( t_i \) are

\[ t_i = t_{i-1} + \Delta t \quad \ldots \ldots \ldots \ldots \ldots \quad (93) \]

\[ \{q\}_i = \{q\}_{i-1} + \{AY\} \quad \ldots \ldots \ldots \ldots \ldots \quad (94) \]

\[ \{\dot{q}\}_i = \{\dot{q}\}_{i-1} + \{AZ\} \quad \ldots \ldots \ldots \ldots \ldots \quad (95) \]

This solution is continued using previous values of \( \{q\} \) and \( \{\dot{q}\} \) to solve for those at the next time step.

**The Computer Program**

The computer program was written in FORTRAN IV on the Amdahl 470 V/6. A LISTING OF THE COMPUTER PROGRAM is given and the input documentation is given in DESCRIPTION OF INPUT TO THE COMPUTER PROGRAM.

**The Subroutines**

MAIN controls the logic flow of the program. Subroutines DATAIN, INITL, LOCATE, ECHO, STEPS, RKSOLN, ACCEL, ENDFRC, and OUTPUT are called from this routine.

Subroutine DATAIN reads all of the required data for the program. Subroutine INITL initializes the values of the barrier geometry and velocity, and converts all input into a ft-lb-sec-rad system of units. Subroutine ECHO prints out the input data read in DATAIN.
Subroutine RKSOLN performs the Runge-Kutta integration and calculates the new global coordinates and velocities at each time step. It calls subroutine STEPS. Subroutine STEPS generates the equations of motion and solves for the generalized accelerations. It calls subroutines LOCATE, TRNVEL, FORCE, DMTRX, EMTRX, FSMTRX, QEMTRX, QFMTRX, ADD, and GAUSS.

Subroutine LOCATE calculates the global coordinates of each barrier segment end point.

Subroutine TRNVEL calculates the translational velocity components for each segment center of mass. Subroutine FORCE locates the impact force and determines its magnitude using linear interpolation of the input data.

Subroutine DMTRX generates the $[D]$ matrix from barrier segment properties and geometry at each time step. Subroutine EMTRX calculates the elements in each row of the $\{E\}$ column vector. Subroutine FSMTRX determines the contributions of potential energy in the joint springs to $\{F_s\}$.

Subroutine QEMTRX finds the generalized force in $\{Q_e\}$ due to the impact force on the barrier segment. Subroutine QFMTRX calculates the friction force contributions to the generalized forces in $\{Q_f\}$.

Subroutine ADD sums the $\{E\}$, $\{F_s\}$, $\{Q_e\}$, and $\{Q_f\}$ column vectors into $\{R\}$. Subroutine GAUSS solves for the generalized accelerations for a given $[D]$ and $\{R\}$ using Gaussian elimination for simultaneous equations.

Subroutine ACCEL calculates the segment center of mass accelerations using the generalized velocities and accelerations. Subroutine ENDFRC determines the member end forces on each segment due to imposed
loads and accelerations. Subroutine OUTPUT prints out barrier geometry, accelerations, and end forces at each required time step.

Output

The user can request output at any time interval desired with the proper variable input. At each time step the following information is printed:

1. The global coordinates of the end points of each barrier segment;
2. The angular rotation of each barrier segment in the fixed coordinate system;
3. The components of each center of mass acceleration in the fixed coordinate system;
4. The global angular acceleration of each barrier segment;
5. The forces and moments at the ends of each barrier segment in its segment fixed coordinate system.
VALIDATION OF BARRIER MODEL

Initial Checkout

Once the equations of motion for the system had been derived, a three-step procedure was used to validate and check the coded program. These steps were a general check of matrix assembly and solution scheme logic, comparison with known solutions of theoretical problems, and simulation of previous crash tests.

After debugging was completed, the first phase of verification began. The program's results for each of the assembled matrices was checked against long-hand calculations using the equations in EQUATIONS OF MOTION. At the same time the Gauss solution scheme for linear equations and the Runge-Kutta integration technique were verified with independent tests. Finally, the matrix assembly, time integration, and elimination routines were linked into a single program and checked for stability after one time step.

Idealized Structure Modeling

Once the program was running correctly on a single time increment, the second set of checks was performed. Two idealized structures systems were modeled and run to examine exactness with theoretical solutions. The first was a single member pinned at one end and subjected to a constant force, as shown in Figure 11. By setting $M_1$, $u_1$, and $I_{01}$ very large in comparison to $M_2$, $u_2$, and $I_{02}$ and using no spring at the joint, this model showed a good relationship with the theoretical solution. Table 1 shows the values used for each of the variables and the results of each analysis.
Figure 11. Idealized and Modeled Structures for First Theoretical Study.
Table 1. Input and Results from First Idealized Simulation.

<table>
<thead>
<tr>
<th>Input</th>
<th>Idealized Structure</th>
<th>Modeled Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$ (lb-sec$^2$/ft)</td>
<td>Fixed,</td>
<td>6217.6</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>not</td>
<td>1.0</td>
</tr>
<tr>
<td>$I_{01}$ (ft-lb-sec$^2$)</td>
<td>required</td>
<td>82901.</td>
</tr>
<tr>
<td>$M_2$ (lb-sec$^2$/ft)</td>
<td>248.45</td>
<td>248.45</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>--</td>
<td>0.0</td>
</tr>
<tr>
<td>$I_{02}$ (ft-lb-sec$^2$)</td>
<td>8281.7</td>
<td>8281.7</td>
</tr>
</tbody>
</table>

Results

- Acceleration: 0.906 (rad/sec$^2$) (Constant)
- Angular Displacement at Time=0.10 sec: 0.260°
- $\Delta t=0.001$ sec
- $\dot{\epsilon}_t=0.10$ ft/sec
- $\dot{\epsilon}_R=0.05$ rad/sec
In the second idealized case, an elastic spring was added to the same structure with altered mass and moment of inertia values and the element was given an initial rotation. By using the stiffness and mass moment of inertia to find the natural frequency, the time for the segment to return to its initial position can be calculated. As in the first test, the program showed very good results in comparison to the idealized solution. These results are listed in Table 2.

At this point it should be noted that the three adjustable parameters were established during this phase of the research. The time increment for stability in the first test was 0.001 secs. This worked in the second analysis, and was maintained throughout the remainder of the computer runs. The translational adjustment for friction was set at 0.1 ft and the rotational adjustment was 0.05 rad. These values were also used in all subsequent simulations.

**Crash Test Simulation**

In the final step of the validation, six previous crash tests on concrete median barriers were selected (2, 3, 4, 5). Each of these tests used a barrier that could be modeled with the proper selection of parameters to represent the system. On-going research (3) has established the joint properties in terms of rotations and moment capacities. Table 3 summarizes the necessary values to define the barrier and joint properties. In all cases, the barrier segments were initially straight.

The force input was the most difficult variable to establish. Tests CMB-2, CMB-24, NY-1, and NY-2, were standard structural adequacy tests (6). Force versus time data for a structural adequacy test were experimentally determined by Bronstad (7).
This input is recorded in the table in DESCRIPTION OF INPUT TO THE COMPUTER PROGRAM. A rough estimate was made from vehicle accelerometer and film data for use in the other two tests, CAL-291 and CAL-294. Table 4 gives this input. With the proper barrier and joint properties, system geometry and external forces calculated, the various tests were simulated with varying success. The results and problems are summarized below.

Table 5 and Figure 12 show the values of absolute maximum lateral deflection for the actual crash test and those predicted by computer simulation. With the exception of tests NY-1 and NY-2, the comparison was very good. There were several factors in the NY tests that could not be exactly determined, and they likely contributed to this difference. The number of barrier segments and location of the vehicle impact point were unknown. Six segments were assumed to eliminate system end point movement. An impact at the center of the third segment was assumed for these two tests, since this seemed to be the most severe point. Further, the type of surface the barriers were erected on was unknown. If a grout bed or hot asphalt mix was used as a leveling course, the value of friction at the roadway would have to be much larger. It should be noted here that a friction coefficient of 1.0 was used on CMB-2 because it was built on a hot mix asphalt bed.

Finally, vehicle impact conditions for the NY tests (as well as the other tests) varied from the conditions used in the Bronstad test (7).
<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Force (lb)</th>
<th>Position (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>41.0</td>
</tr>
<tr>
<td>0.01</td>
<td>18950.</td>
<td>41.95</td>
</tr>
<tr>
<td>0.06</td>
<td>18950.</td>
<td>46.68</td>
</tr>
<tr>
<td>0.065</td>
<td>24300.</td>
<td>47.15</td>
</tr>
<tr>
<td>0.10</td>
<td>0.0</td>
<td>50.46</td>
</tr>
<tr>
<td>0.15</td>
<td>24300.</td>
<td>55.19</td>
</tr>
<tr>
<td>0.20</td>
<td>0.0</td>
<td>59.92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Force (lb)</th>
<th>Position (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>70.8</td>
</tr>
<tr>
<td>0.01</td>
<td>18800.</td>
<td>71.7</td>
</tr>
<tr>
<td>0.10</td>
<td>18800.</td>
<td>80.1</td>
</tr>
<tr>
<td>0.11</td>
<td>0.0</td>
<td>82.0</td>
</tr>
<tr>
<td>0.27</td>
<td>0.0</td>
<td>98.0</td>
</tr>
<tr>
<td>0.29</td>
<td>35250.</td>
<td>100.1</td>
</tr>
<tr>
<td>0.34</td>
<td>35250.</td>
<td>105.2</td>
</tr>
<tr>
<td>0.36</td>
<td>0.0</td>
<td>107.3</td>
</tr>
</tbody>
</table>
Table 5. Simulation Results of Previous CMB Crash Tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Observed Maximum Deflection (ft)</th>
<th>Predicted Maximum Deflection (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAL-291</td>
<td>0.52</td>
<td>0.65</td>
</tr>
<tr>
<td>CAL-294</td>
<td>0.46</td>
<td>0.61</td>
</tr>
<tr>
<td>NY-1</td>
<td>1.33</td>
<td>3.63</td>
</tr>
<tr>
<td>NY-2</td>
<td>0.92</td>
<td>2.09</td>
</tr>
<tr>
<td>CMB-24</td>
<td>3.42</td>
<td>3.49</td>
</tr>
<tr>
<td>CMB-2</td>
<td>1.10</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Figure 12. Predicted versus Observed Deflections for Six Crash Test Simulations.
PARAMETRIC STUDY OF BARRIER RESPONSE

Since the precast concrete median barrier has so many design configurations, the various effects of barrier length, joint moment capacity, joint rotational slack, and roadway friction on lateral reflection of the barrier due to vehicle impact were all studied. Each parameter was varied independently to give some insight into each of their effects. The results of this study will be used later in the design phase of this report.

Before the parameter study began three barrier lengths were identified as the most desirable, 12 ft, 20 ft, and 30 ft, since they have been used in previous designs. This was not a restrictive assumption, but was made initially to establish a starting point. Other lengths were also considered later.

The force vs. time input for the structural adequacy test of longitudinal barriers (a 4500 lb vehicle traveling at 60 mph with a 25° encroachment angle) was used in the parameter study. In all parameter runs, the impact was located approximately at the third point of the system. The input for this impact is given in the table in the DESCRIPTION OF INPUT TO THE COMPUTER PROGRAM.

Analysis for Length of Need and Impact Location

With the necessary forcing function established, two important questions had to be resolved. How many segments are necessary to eliminate significant end point movement, and, is an impact at the joint or the center of the barrier more critical? Significant end point movement was arbitrarily defined as greater than 2 in. of displacement at each
Figure 14. Lateral Joint Displacement Versus Connection Moment, Variable Segment Length.
Effects of Joint Connection Slack on Lateral Displacements

The relationship of joint connection slack to barrier displacement was investigated next. In this series of simulations, connection slack was varied from 1 deg to 8 deg for all five barrier lengths. The ultimate moment was held constant at 100 k-ft and the elastic limit, $\phi_e$, was always 2 deg larger than the slack rotational limit, $\phi_s$. This was done to keep the elastic spring constant, $k_E$, the same for all tests. As in previous studies, the friction coefficient was $\mu = 0.7$. The results are summarized in Table 8 and are plotted in Figure 15.

The curves in Figure 15 show a general increase in deflection as the connection slack grows. However, examination of the individual curves shows some correlation with the results of the previous work on moment capacity. The 30 ft length shows the least increase in deflection of the five, and the 25 ft length follows the general upward trend with no irregularities. This is primarily due to the fact that these segment lengths generate their resisting forces with friction and not joint moments. It can be noted that while there is little difference between the two lengths for slack less than 3 deg, the displacement in the 25 ft length begins to grow faster at a slack larger than 3 deg. The 12 ft, 15 ft, and 20 ft segment lengths also show the general trend of increasing lateral deflections with increasing amounts of joint slack. The 20 ft length shows the most rapid increase in displacement at a slack of 3 deg or greater when compared to all other lengths and joint slack values. A slack up to 5 deg has very little affect on the 15 ft length, but lateral displacements grow very quickly once slack increases.
Table 8. Connection Slack-Segment Length-Deflection Study Results.

\[ \mu = 100 \text{ k-ft} \quad \phi_e = \phi_s + 2^0 \]

<table>
<thead>
<tr>
<th>LENGTH (ft)</th>
<th>SLACK (deg)</th>
<th>LATERAL DISPLACEMENT (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.20</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.99</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.34</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.53</td>
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<tr>
<td></td>
<td>5</td>
<td>1.75</td>
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<td>8</td>
<td>1.86</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.43</td>
</tr>
</tbody>
</table>
\[ M_u = 100 \text{ k-ft} \]
\[ \phi_e = \phi_s + 2^\circ \]
\[ \mu = 0.7 \]

**Figure 15.** Lateral Joint Displacement Versus Connection Slack, Variable Segment Length.
beyond 5 deg. The same type of response is seen in the 12 ft segment lengths. The maximum deflection of the 12 ft length is larger than that for the 15 ft length at all values of connection slack studied. However, for connection slack greater than 3 deg, the 12 ft length showed smaller deflections than for a corresponding amount of slack on a 20 ft segment. Once again, the 20 ft length shows the largest deflections at most values of joint slack.

Effects of Friction

on Lateral Displacements

The final parameter to be analyzed was the effects of the friction coefficient on barrier displacement. This study was limited to lengths of 12 ft, 15 ft, and 20 ft for two reasons. First, lengths in excess of 20 ft were not considered portable enough to warrant further study. Also, the shorter lengths had previously shown the greatest response to joint moment and slack variation and were considered the most likely to show the same response. These three lengths were then singled out for continued study. A joint with moment capacity of 150 k-ft, a slack rotation of 1 deg, and an elastic limit at 3 deg was used in all tests. The friction coefficient was varied from 0.4 to 0.6. The results are given in Table 9 and displayed in Figure 16.

None of these results can be considered surprising. As the friction value decreased for each segment length, the lateral displacement increased slightly. Since the resisting friction force is proportional to the coefficient, this simply indicates that the short segment lengths are not affected very much by changes in the friction force.
Table 9. Friction Variation Study Results.

\[ \phi_s = 1^\circ \quad \phi_e = 3^\circ \quad M_u = 150 \text{ k-ft} \]

<table>
<thead>
<tr>
<th>LENGTH (ft)</th>
<th>FRICTION COEFFICIENT ( (\mu) )</th>
<th>LATERAL DEFLECTION (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.4</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.50</td>
</tr>
<tr>
<td>15</td>
<td>0.4</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.52</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.20</td>
</tr>
</tbody>
</table>
Figure 16. Lateral Joint Displacement Versus Segment Length, Variable Friction.
Analysis with Large Joint Moment Capacity
and Moderate Friction

Before this part of the research was finished, there was additional interest in the effects of a high moment capacity joint with a moderate amount of friction. Three moment capacities, 50 k-ft, 100 k-ft, and 150 k-ft were selected for study. A joint with 1 deg of slack and 3 deg of elastic rotation was used, along with a friction coefficient of 0.5. Once again only 12 ft, 15 ft, and 20 ft segment lengths were used in the analysis. The displacements are given in Table 10 and are also plotted in Figures 17 and 18.

These two figures summarize the important factors to be used in the design stage. First, at 100 k-ft of moment capacity, all barriers experience approximately the same movement. At lesser joint capacities the 12 ft length shows the smallest deflection, and at 150 k-ft, the 20 ft length begins to look best. Finally, the range of 100 to 150 k-ft for joint moment capacities appears to be the maximum the 12 ft and 15 ft segments can utilize. The 20 ft length still shows a decreasing trend at 150 k-ft and may be able to use more available moment at the joint.
Table 10. Additional Results of Joint Moment-Segment Length-Deflection Study.

\[ \phi_s = 1^\circ \quad \phi_e = 3^\circ \quad \mu = 0.5 \]

<table>
<thead>
<tr>
<th>LENGTH (ft)</th>
<th>CONNECTION MOMENT (k-ft)</th>
<th>LATERAL DISPLACEMENT (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>50</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.61</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.60</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Figure 17. Lateral Joint Displacement Versus Segment Length, Variable Connection Moment and Moderate Friction.
Figure 18. Lateral Joint Displacement Versus Connection Moment, Variable Length and Moderate Friction.

Friction Coefficient \( \mu = 0.50 \)
EQUATIONS OF MOTION

\[
[D] \{q\} = \{E\} + \{F_s\} + \{Q_e\} + \{Q_f\} \tag{96}
\]

The above matrix equation defines a set of "n+2" nonlinear, second-order, simultaneous differential equations that describe the motion of the individual barrier segments.

Matrices \([D]\) and \([E]\) result directly from operations with the kinetic energy terms; \([D]\) may be thought of as a pseudo-mass matrix and \([E]\) as an inertial force matrix.

Column vector \(\{F_s\}\) contains generalized forces due to potential energy in the rotational joint springs.

Column vector \(\{Q_f\}\) contains generalized forces produced by friction between the barrier and the roadway.

Column vector \(\{Q_e\}\) contains generalized forces resulting from external forces (impact loads).

Following are the expressions to calculate the \([D]\) matrix:

For the diagonal terms,

\[
D_{1,1} = \sum_{i=1}^{n} M_i \tag{97}
\]

\[
D_{2,2} = \sum_{i=1}^{n} M_i \tag{98}
\]

\[
D_{i,i} = \rho_i^2 M_i + L_i \sum_{j=i+1}^{n} M_j \quad \text{For } i = 1, 2, \ldots, n-1 \tag{99}
\]

\[
D_{i+2,i+2} = \rho_n^2 M_n \quad \text{For } i = n \tag{100}
\]
For the remaining row one terms,

\[ D_{1,2} = 0 \]  \hspace{1cm} (101)  \\
\[ D_{1,i} = \rho_i M_i \sin \phi_i - L_i \sin \phi_i \sum_{j=i+1}^{n} M_j \]  \hspace{1cm} \text{For } i = 1, 2, \ldots, n-1 \hspace{1cm} (102)  \\
\[ D_{1,i+2} = -\rho_n M_n \sin \phi_n \]  \hspace{1cm} \text{For } i = n \hspace{1cm} (103)  \\

For row two terms,

\[ D_{2,i+2} = \rho_i M_i \cos \phi_i + L_i \cos \phi_i \sum_{j=i+1}^{n} M_j \]  \hspace{1cm} \text{For } i = 1, 2, \ldots, n-1 \hspace{1cm} (104)  \\
\[ D_{2,i+2} = \rho_n M_n \cos \phi_n \]  \hspace{1cm} \text{For } i = n \hspace{1cm} (105)  \\

For row 3 to row \( n+1 \)

\[ D_{i+2,j+2} = L_{i} \cos(\phi_{i} - \phi_{j})(\rho_{j} M_{j} + L_{j} \sum_{k=j+1}^{n} M_{k}) \]  \hspace{1cm} \text{For } i = 1, 2, \ldots, n-1, \ldots \hspace{1cm} (106)  \\
\hspace{3.5cm} j = 1, 2, \ldots, n-1  \\

For \( n+2 \) column,

\[ D_{i+2,n+2} = L_{i} \rho_{n+2} M_{n+2} \cos(\phi_{i} - \phi_{n+2}) \]  \hspace{1cm} \text{For } i = 1, 2, \ldots, n \hspace{1cm} (107)  \\

\( [D] \) is a symmetric matrix, so it is only necessary to calculate half of the matrix, and then set

\[ D_{ji} = D_{ij} \]  \hspace{1cm} \text{For } j = 2, 3, \ldots, n-12 \hspace{1cm} (108) \hspace{1cm} i = 1, \ldots, j-1  \\

Following are the elements for column vector \( \{ E \} \):

For row one

\[ E_1 = \sum_{i=1}^{n} \phi_i^2 \cos \phi_i \rho_i M_i + L_i (\sum_{j=i+1}^{n} M_j) \hspace{1cm} \ldots \ldots \hspace{1cm} (109) \]

For row two term,

\[ E_2 = \sum_{i=1}^{n} \phi_i^2 \cos \phi_i \rho_i M_i + L_i (\sum_{j=i+1}^{n} M_j) \hspace{1cm} \ldots \ldots \hspace{1cm} (110) \]
Remaining terms, rows 3 through n+2,

\[ E_{i+2} = \sum_{j=1}^{i-1} L_j \phi_j^2 \sin(\phi_j - \phi_i) \left( \rho_j M_i + L_j \sum_{k=i+1}^{n} M_k \right) + L_i \sum_{j=i+1}^{n} M_j \phi_j^2 \sin(\phi_j - \phi_i) \]

\[ + L_i \sum_{j=i+1}^{n} L_j \phi_j^2 \sin(\phi_j - \phi_i) \sum_{k=j+1}^{n} M_k \] ....... (111)

Note that the first term is not included in the \( E_3 \) calculation, the second term is not included in the \( E_{n+2} \) calculation, and the third term is not a part of the \( E_{n+1} \) or \( E_{n+2} \) calculation.

Following are the elements for column vector \( \{ F_s \} \):

\[ F_{s_1} = 0 \] ................. (112)

\[ F_{s_2} = 0 \] ................. (113)

\[ F_{s_{i+2}} = -M_{u_i} \] For \( i = 1 \) .......... (114)

\[ F_{s_{i+2}} = M_{u_{i-1}} - M_{u_i} \] For \( i = 2, 3, \ldots n-1 \) .......... (115)

\[ F_{s_{i+2}} = M_{u_{i-1}} \] For \( i = n \) .......... (116)

where \( M_{u_i} \) is the moment in spring "i". This value is dependent on the particular response range the spring has been deformed to and the spring's previous loading history. This relationship or spring moment to displacement is shown in Figure 7 of the main body of this appendix.

Following are the elements of the \( \{ Q_e \} \) column vector:

For a force located on segment \( j \)

\[ Q_{e_1} = -F_y \tan j \] ................. (117)

\[ Q_{e_2} = F_y \] ................. (118)
\[ Q_{e_{i+2}} = Fy' L_i (\cos \phi_i + \sin \phi_i \tan \phi_j) \quad \text{For } i = 1, 2, \ldots, j-1 \quad (119) \]

\[ Q_{e_j} = Fy' \sec^2 \phi_j (X_{i}^F - X_{i}^R) \quad \ldots \ldots \ldots \ldots \ldots \quad (120) \]

\[ Q_{e_{i+2}} = 0 \quad \text{For } i > j \quad \ldots \ldots \ldots \quad (121) \]

Following are the elements for the \( \{Q_f\} \) column vector:

\[ Q_{f_1} = - \sum_{i=1}^{n} C_{ti} \frac{\dot{X}_i}{R_i} \hat{w}_i \quad \ldots \ldots \ldots \ldots \ldots \quad (122) \]

\[ Q_{f_2} = \sum_{i=1}^{n} C_{ti} \frac{\dot{Y}_i}{R_i} \hat{w}_i \quad \ldots \ldots \ldots \ldots \ldots \quad (123) \]

\[ Q_{f_{i+2}} = C_{ti} \frac{\dot{R}_i \hat{w}_i}{R_i} \chi_i^j \sin \phi_i + \dot{Y}_i^j \cos \phi_i \]

\[ + L_i \sum_{j=i+1}^{n} C_{tj} \frac{\hat{w}_i^j}{R_j} X_j^i \cos \phi_i + \dot{Y}_j^i \sin \phi_i \]

\[ - C_{ri} \frac{1}{\phi_i} \frac{\hat{w}_i^r L_i}{4} \quad \text{For } i = 1, 2, \ldots, n \quad (124) \]
LISTING OF THE COMPUTER PROGRAM

REAL PHI(15), PHIO(15), PHID(15), PHM(15)
REAL XE, KP, KL, M, L, I0
CHARACTER*80 HEAD1, HEAD2
COMMON /TITLE/ HEAD1, HEAD2
COMMON/XMEMBER/ X(15), P(15), L(15), (0(15), U(15), W(15)
COMMON /SPRING/ PHIS,PHIO,PHID,PHF,KE,KP,KL,ENEM,PMON
+PHI(14),KEY(14),DPHI(14)
COMMON /ENOPT/ XI(15), YI(15), XT(15), YT(15)
COMMON /CGPROP/ XD(15), YO(15), X0(15), Y0(15)
COMMON /MATRIX/ D(17,18), E(17), F3(17), QE(17), SF(17)
COMMON /CONST/ N, NP1, NP2, NMI, NPROT, MAXK, INDEX, DT, ER, DP
COMMON /IMPACT/ TMPT(50), XPT(50), FPT(50), NPTS, IAT, XF, XNO=
+CF, FY, RDP
COMMON /ALPHAS/ AYO(17), AZD(17), QD(17)
COMMON /MAXDIS/ DEFL, NQPT, TIMEX
EQUIVALENCE (E(1),RMS(1))
PI = A=ATAN(1,0)
1 CALL DAIN0 (XRO,YRO,PHIO)
IF (N.EQ.0) GO TO 100
NP2 = N + 2
NP1 = N + 1
NMI = N + 1
KPT = 1
CALL INITL (PHI,PHIO,PHID,XR,XRO,XR0,YR0,YRO,YRO,TIME)
CALL LOCATE (XR,YR,PHI,TIME)
CALL ECHO (PHIO)
AYD(1) = XR
AYD(2) = YR
AZD(1) = XRO
AZD(2) = YRO
DO 5 K = I,N
XP2 = K + 2
AYD(KP2) = PHI(K)
AZD(KP2) = PHID(K)
5 CONTINUE
CALL STEPS (TIME)
NOT = 0
NTIME = TMPT(NPTS)/DT * 0.001
DO 75 NSTEP = 1, NTIME
CALL PKSOLN (XR,YR,PHI,XRO,YRO,PHID,TIME)
IF (MARK.GT.0) GO TO 100
IF (INDEX.EQ.1) GO TO 100
NOT = NOT + 1
TIME = TIME + DT
IF (NOT .LT. NQPT) 75, 60, 60
75 CONTINUE
DEFL = DEFL + 12.0
WRITE (6,630) DEFL, NQPT, TIMEX
GO TO 1
100 WRITE (6,699)
STOP
630 FORMAT ('**TABULATION MAXIMUM DEFORMATION = ',F9.2,' INCHES
+AT END POINT NUMBER ',I5,' AT TIME = ',F7.3,' SEC')
699 FORMAT ('**TABULATION MAXIMUM DEFLECTION = ',F9.2,' INCHES
+AT END POINT NUMBER ',I5,' AT TIME = ',F7.3,' SEC')
SUBROUTINE DATA

COMMON /HEAD1, HEAD2
COMMON /CONST/ N,NP1,NP2,NM1,NPRT,MARK,INDEX,DT,ET,ER,P
COMMON /MEMBER/ M(15), P(15), L(15), IO(15), U(15), K(15)
COMMON /Spring/ XRO,YRO,PHIE,PHIP,PHIF,KE,KP,KL,EMON,PROM

COMMON /IMPACT/ TMPT(50), XPT(50), FPT(50), NPTS, NPT, XF, YF, ZX, ZY
COMMON /MARK/ Q1(15), Q2(15), Q3(15), Q4(15), Q5(15), Q6(15)
COMMON /MARKS/ DEFL, NORT, TIMEX
REAL PHI(15), PH10(15), PHID(15)
REAL KE, KP, KL, M
XF = 0.0
YF = 0.0

C = INITIALIZE THE BARRIER POSITION AND CONVERT PHI TO RADIANS
XR = XRO
YR = YRO
DO 20 I = 1,N
PHI(I) = PHI(I)/180.0*PI
20 CONTINUE
C = SET THE INITIAL VELOCITIES TO ZERO
XR = 0.0
YR = 0.0
DO 30 I = 1,N
PHI(I) = 0.0
30 CONTINUE
C = CALCULATE THE BARRIER HEIGHTS FROM THE MASS VALUES
DO 40 I = 1,N
\begin{verbatim}
* 40 CONTINUE
C * INITIALIZE JOINT SPRING PROPERTIES
  EJM0N = KE*(PH1S-PH1S)
  PH0M = KP*(PH1-PH1E)
  DO 50 I = 1,NM1
    IP1 = I + 1
    OPH1(I) = PH1(I) - PH1(1)
    PH2(I) = 0.0
  KEY(I) = 0
50 CONTINUE
C * SET MEMBER END FORCES OF BARRIER ONE TO ZERO
  Q1(1) = 0.0
  Q2(1) = 0.0
  Q3(1) = 0.0
  Q(N) = 0.0
RETURN
END

SUBROUTINE ECHO (PH10)
COMMON /TITLE/ HEA01, HEA02
COMMON /MEMBR./ Y(I),15), U(I),15), X(I)
COMMON /CONST/ MP1, MP2, NAM1, NDIPK, LMK, INDEX, D T,CT,ST
COMMON /EMOPT/ XI(15), YI(15), XI(15), YI(15)
COMMON /SPRING/ PH1S, PH1E, PH1P, PH1F, KE, KP, KL, EJM0N, PH0M
  PH1Z14), KEY(14), DPHI(14)
COMMON /IMPACT/ THM(50), XPT(50), NPT(50), WPTS, [PT, X, Y, X
  CF, F, PY
C CHARACTER=60 HEA01, HEA02
REAL PH10(I)
REAL KE, KP, KL, M, L, 10
WRITE (6,600) HEA01, HEA02
WRITE (6,610) (1, M(I), L(I),I0(I), U(I), 1=M, N)
WRITE (6,620)
WRITE (6,630) (1,PH10(I),XI(I),YI(I),XT(I),YT(I), 1=M, N)
WRITE (6,640) ET, ER
WRITE (6,650)
WRITE (6,660) (THM(J), XPT(J), NPT(J), WPT, X, Y, X
WRITE (6,670) PH1S, PH1E, PH1F, KE, KP, KL
C * CONVERT THE STIFFNESS TO FT-LB/RADIAN
KE = KE*180./PI
KP = KP=180./P
KL = KL=180./PI
C * ADJUST THE ANGLE CHECK VALUES TO RADIANS
PH1S = PH1S*PI/180.
PH1E = PH1E*PI/180.
PH1P = PH1P*PI/180.
RETURN
END

600 FORMAT ('I',5X,A80 / 5X,A80 // +10X,'ELEMENT PROPERTIES FOR SEGMENTAL CONCRETE MEDIAN' + 'BARRIER SYSTEM' / T20,'ELEMENT',T54,'MOMENT OF',T60,'3\#M(\#S' + 'T22,'NO. ',T32,'MAD',T42,'LENGTH',T55,'INERTIA',T66,'FFCTION')+
610 FORMAT ('I',20X,'2.5X,F9.3,5X,F6.2,5X,F9.3,5X,F5.3)
620 FORMAT ('I',30X,'INITIAL POSITION FOR SEGMENTAL BARRIER SYSTEM',+
  // T20,'ELEMENT',T44,'INITIAL END',T68,'TERMINAL END' / T22,'NO.'+
  + 'T32,'X',T42,'Y',T55,'X',T66,'Y',T77,'X',T87,'Y',T97,'X'
630 FORMAT ('I',10X, 'T10.50(***') / T10,'TRANSATIONAL ADJUSTMENT FOR FR(CT1+
  *ON 1=',F10.2 // T10,'ROTATIONAL ADJUSTMENT FOR FR(CTION=',F10.2,+
  'F10.2 / T10.50(***')
650 FORMAT ('I',10X,'TIME=DISPLACEMENT-FORCE INPUT' / T13,'TIME',T25,+
  'OR ION',T37,'FORCE' / T13,'SEC',T25,'(FT)',T37,'(LBS)' / T12,+
  'T13(***')
670 FORMAT ('I',20X,'ELEMENT PROPERTIES' / T12, 'J5(***') // T15,+
  'JOINT ROTATION IVS',T20,'SLACK UP TO',T35,'F3.2 / T20,'ELASTIC JPD' + 'PI,F6.2 / T20,'PLASTIC UP TO',F6.2 / T20,'FAILURE AT',T35,'F6.2,+
  'T15,'ELASTIC STIFFNESS='+,F10.2 / T15,'PLASTIC STIFFNESS=',F10.2 / T13,+
  'LOCK-UP STIFFNESS=',F10.2 / T12, 'J5(***')
END
\end{verbatim}
SUBROUTINE RKSONI (XR, VR, PHI, XROI, YROI, PHI1, TIME)
COMMON /ALPHAS/ AYO(17), AZI(17), ODD(17)
COMMON /CONST/ NNP1, NN2, NNP2, NNR2, NNPRT, MARK, INDEX, OT, ET, SR, PI
REAL PHI(15), PHI1(15)
REAL AYO(17), AZI(17), ODD(17)
AY(1) = DT*XR
AY(2) = DT*YR
DO 10 K = 1, NNP2
KM2 = K - 2
AY(K) = DT*PHI(KM2)
10 CONTINUE
DO 20 K = 1, NNP2
AZ(K) = DT*ODD(K)
20 CONTINUE
DO 30 K = 1, NNP2
AYY(K) = AY(K)/6.0
AZZ(K) = AZ(K)/6.0
30 CONTINUE
DO 50 J = 2, 4
FRAC = 0.5
IF (J.EQ.4) FRAC = 1.0
AYD(1) = XR + FRAC*AY(1)
AYD(2) = YR + FRAC*AY(2)
AZD(1) = XRO + FRAC*AZ(1)
AZD(2) = YRO + FRAC*AZ(2)
DO 40 K = 1, NNP2
KM2 = K - 2
AYD(K) = PHI(KM2) + FRAC*AY(K)
AZD(K) = PHI1(KM2) + FRAC*AZ(K)
40 CONTINUE
TMINC = TIME + DT*FRAC
CALL STEPS (TMINC)
IF (MARK.GT.0) GO TO 100
IF (INDEX.EQ.1) GO TO 100
DO 60 I = 1, NNP2
AY(1) = DT*AZD(I)
AZ(1) = DT*ODD(I)
AYY(I) = AYY(I) + AY(I)/(6.0*FRAC)
AZZ(I) = AZZ(I) + AZ(I)/(6.0*FRAC)
60 CONTINUE
DO 80 K = 1, NNP2
KM2 = K - 2
PHI(KM2) = PHI(KM2) + AY(K)
PHI1(KM2) = PHI1(KM2) + AZ(K)
80 CONTINUE
100 RETURN
END
SUBROUTINE STEPS (TIME)
COMMON /APIMAS/ AYO(17), AZD(17), GEO(17)
COMMON /CONST/ N, NP1, NP2, NML, NPRT, MK, INDEX, OT, ET, ER, PI
REAL XD(15), YD(15), PHI(15), PHI(15), PHI(15), PHI(15)
EQUIVALENCE (AYO(1), XR), (AYO(2), YR), (AZD(1), XR), (AZD(2), YR)
EQUIVALENCE (AYO(3), PHM(1)), (AZD(3), PHM(1))
C EQUIVALENCE (RMS, GEO)
COMMON /MATRX/ Q(17, 18), RHS
CALL LOCATE (XR, YR, PHI, TIME)
CALL FORCE (TIME)
CALL DMTRX (PHI)
CALL EMTRX (PHM, XRD, YRD)
CALL FSMTRX (PHI)
CALL GMTRX (PHI)
IF (MARK.GT.0) GO TO 100
CALL GSMTRX (PHM, PHID)
CALL ADD
CALL GAUSS (GEO)
100 RETURN
END

SUBROUTINE LOCATE (XR, YR, PHI, TIME)
COMMON /CONST/ N, NP1, NP2, NML, NPRT, MK, INDEX, OT, ET, ER, PI
COMMON /MEMBER/ Y(15), P(15), L(15), I(15), II(15), #1(15)
COMMON /MAXDIS/ DEFL, NOPT, TIMEMX
COMMON /ENOPT/ XI(15), YI(15), XT(15), YT(15)
REAL PHI(15), L
C = CALCULATE X-COORDINATES OF SEGMENT ENDPOINTS
XI(1) = XR
DO 20 J = 1, NMI
JP1 = J + 1
XI(JP1) = XI(J) + COS(PHI(J))*L(J)
XT(J) = XI(JP1)
20 CONTINUE
XT(N) = XI(N) + COS(PHI(N))*L(N)
C = CALCULATE Y-COORDINATES OF SEGMENT ENDPOINTS
YI(1) = YR
DO 40 J = 1, NMI
JP1 = J + 1
YI(JP1) = YI(J) + L(J)*SIN(PHI(J))
YT(J) = YI(JP1)
40 CONTINUE
YT(N) = YI(N) + SIN(PHI(N))*L(N)
C = CHECK FOR MAXIMUM ENDPOINT DISPLACEMENT
DO 60 I = 1, N
IF (ABS(YI(I)) - DEFL) 60, 55, 55
55 DEFL = ABS(YI(I))
NOPT = I
TIMEMX = TIME
60 CONTINUE
IF (ABS(YT(N)) - DEFL) 70, 65, 65
65 DEFL = ABS(YT(N))
NOPT = N + 1
TIMEMX = TIME
70 CONTINUE
RETURN
END
SUBROUTINE TRAVEL (XRO,YRO,PHID,PHI)
COMMON /MEMBER/ A(15), P(15), L(15), O(15), U(15), W(15)
COMMON /CCNST/ N, NP1, NP2, NM1, NM2, NPRT, MPAR, INDEX, JT, ET, EP1
COMMON /CGPROP/ XD(15), YD(15), XO(15), YO(15), X0(15), Y0(15)
REAL PHI(15), PHID(15), L
C   * FIND CENTER OF MASS TRANSLATIONAL VELOCITY IN GLOBAL X-DIRECTION
DO 50 I = 1,N
   XD(I) = XRO - P(I)*SIN(PHI(I))*PHID(I)
   IF (I.EQ.1) GO TO 50
   SUM = 0.0
   IMI = I - 1
   DO 40 K = 1,IMI
      SUM = SUM + L(K)*SIN(PHI(K))*PHID(K)
   40 CONTINUE
   XD(I) = XD(I) - SUM
50 CONTINUE
C   * FIND CENTER OF MASS TRANSLATIONAL VELOCITY IN GLOBAL Y-DIRECTION
DO 100 I = 1,N
   YD(I) = YRO + P(I)*COS(PHI(I))*PHID(I)
   IF (I.EQ.1) GO TO 100
   SUM = 0.0
   IMI = I - 1
   DO 90 K = 1,IMI
      SUM = SUM + L(K)*COS(PHI(K))*PHID(K)
   90 CONTINUE
   YD(I) = YD(I) + SUM
100 CONTINUE
RETURN
END

SUBROUTINE FORCE (TIME)
COMMON /IMPACT/ TMPT(SO), XPT(SO), FPT(SO), NPTS, IPT, XF, IMPD
         * CF, FX, FY
C   * FIND RANGE OF TIME TO INTERPOLATE BETWEEN
   [PTP1] = IPT + 1
   IF (TIME.GE.TMPT(IPT) .AND. TIME.LT.TMPT(IPTP1)) GO TO 30
   DO 20 N = IPT,NPTS
      I = N
      IF (TMPT(I) .LE. TIME) .AND. (TMPT(N) .GT. TIME) GO TO 25
   20 CONTINUE
      MARK = 20
      GO TO 100
   25 [PT] = [IPTP1] = [IPT] + 1
C   * FIND CORRESPONDING FORCE AND LOCATION FOR CURRENT VALUE OF TIME
   30 XF = XPT(IPT) + (XPT(IPTP1) - XPT(IPT)) / (TMPT(IPTP1) - TMPT(IPT)) * 
      (TIME - TMPT(IPT))
   FY = FPT(IPT) + (FPT(IPTP1) - FPT(IPT)) / (TMPT(IPTP1) - TMPT(IPT)) * 
      (TIME - TMPT(IPT))
   FX = CF*FX
100 RETURN
END
SUBROUTINE OMTRX (PH)
COMMON /MEMBER/ M(15), P(15), L(15), I0(15), U(15), *(15)
COMMON /MATRIX/ D(17,18), E(17), F(17), Q(17), OF(17)
COMMON /CONST/ N, NP1, NP2, NM1, NPRT, MARK, INDX, JT, ET, ER, PI
REAL PH(15)
REAL M, N, 10
C = CALCULATE DIAGONAL TERMS
  SUM = 0.0
  DO 1 I = 1,N
    SUM = SUM + M(I)
  1 CONTINUE
  DO 10 I = J,NP2
    IM1 = I - 1
    IM2 = I - 2
    DO (1,J) = (D(IM2,M) = 2 * M(IM2) + 10(IM2)
    IF (IM2.GE.N) GO TO 10
    SUM = 0.0
    DO 5 J = IM1,N
      SUM = SUM + M(J)
  5 CONTINUE
  DO (1,J) = O(1,J) + SUM = L(IM2)**2
  10 CONTINUE
C = CALCULATE ROW ONE TERMS
  DO (1,J) = 0.0
  DO 20 J = 3,NP2
    JM1 = J - 1
    JM2 = J - 2
    DO (1,J) = -P(JM2)*M(JM2)
    IF (JM2.GE.N) GO TO 20
    SUM = 0.0
    DO 15 JJ = JM1,N
      SUM = SUM + M(JJ)
  15 CONTINUE
  DO (1,J) = O(1,J) - SUM = L(JM2)
  20 DO (1,J) = O(1,J) = SIN(PH(JM2))
C = CALCULATE ROW TWO TERMS
  DO 30 J = 3,NP2
    JM1 = J - 1
    JM2 = J - 2
    DO (1,J) = P(JM2)*M(JM2)
    IF (JM2.GE.N) GO TO 30
    SUM = 0.0
    DO 25 JJ = JM1,N
      SUM = SUM + M(JJ)
  25 CONTINUE
  DO (1,J) = O(1,J) + SUM = L(JM2)
  30 DO (1,J) = O(1,J) = COS(PH(JM2))
C = CALCULATE REMAINING D MATRIX ELEMENTS
  DO 40 I = 3,NP1
    IP1 = I + 1
    IM2 = I - 2
    DO 50 J = [IP1,NP2
      JM1 = J - 1
      JM2 = J - 2
      DO (1,J) = L(IM2)*P(JM2)*M(JM2)
      IF (JM1.GT.N) GO TO 50
      SUM = 0.0
      DO 45 JJ = JM1,N
        SUM = SUM + M(JJ)
  45 CONTINUE
  DO (1,J) = O(1,J) + SUM = L(IM2)*L(JM2)
  50 DO (1,J) = O(1,J) = COS(PH(JM2) - PHI(IM2))
  DO 60 I = 2,NP2
    IM1 = I - 1
    DO 60 J = 1,IM1
      O(1,J) = O(J,I)
  60 CONTINUE
RETURN
END
SUBROUTINE ECMTRX (PHI, PHIO, XRO, 'TRO, I)

COMMON /MEMBER/ M(15), P(15), L(15), O(15), U(15), G(15)
COMMON /MATRIX/ O(I, 1, I, 1), E(I, 1), F(I, 1), G(I, 1), J(I, 1)
COMMON /CONST/ N, NP, N1, N2, N3, N4, N5, N6, N7, N8, N9, N10
REAL PHI(15), PHIO(15)
REAL L(1, I)

C = CALCULATE ROW ONE TERM

E(1) = 0.0
DO 20 K = 1, N
KPI = K + 1
SUM = 0.0
IF (K.EQ.1) GO TO 15'
DO 10 I = KPI, N
SUM = SUM + M(I)
10 CONTINUE
15 E(1) = E(1) + (L(K) * SUM + P(K) * M(K)) * PHIO(K)**2*COS(PHI(K))
20 CONTINUE

C = CALCULATE ROW TWO TERM

E(2) = 0.0
DO 70 K = 1, N
KPI = K + 1
SUM = 0.0
IF (K.EQ.1) GO TO 65
DO 50 I = KPI, N
SUM = SUM + M(I)
50 CONTINUE
65 E(2) = E(2) + (L(K) * SUM + P(K) * M(K)) * PHIO(K)**2*SIN(PHI(K))
70 CONTINUE

C = CALCULATE REMAINING MATRIX TERMS

80 DO 200 I = 1, N
IPI = I + 1
IP2 = I + 2
E(IP2) = 0.0
PHI = P(I) * M(I)
L1 = L(I)
IF (I.EQ.1) GO TO 135
IM1 = I - 1
SUM = 0.0
IF (I.EQ.N) GO TO 125
DO 120 K = IPI, N
SUM = SUM + M(K)
120 CONTINUE
125 DO 130 J = 1, IM1
E(IP2) = E(IP2) + PHIO(J)**2*L(J) = + SIN(PHI(J) - PHI(I)) * (PHI + L1 * SUM)
130 CONTINUE
IF (I.EQ.N) GO TO 200
135 SUM = 0.0
DO 140 K = IPI, N
SUM = SUM + M(K) * PHIO(K)**2
+ * SIN(PHI(K) - PHI(I))
140 CONTINUE
E(IP2) = E(IP2) + L(I) * SUM
SUM = 0.0
IF (IP2.GE.NM1) GO TO 200
DO 160 J = IP1, NM1
SUM = SUM + L(J) * PHIO(J)**2 * SIN(PHI(J) - PHI(I))
JP1 = J + 1
160 CONTINUE
DO 170 K = JP1, N
PROD = PROD + SUM * M(K)
170 CONTINUE
E(IP2) = E(IP2) + L1 * PROD
160 CONTINUE
200 CONTINUE
RETURN
END
SUBROUTINE FSMTRX (PHI)
COMMON /MATRIX/ Q(17,18), E(17), FS(17), QE(17), QF(17)
COMMON /CONST/ N,NP1,NP2,NM1,NPRD,MARK,INDEX,DT,ET,ER,PI
COMMON /SPRING/ PH1,PHIE,PHIF,KE,KP,KL,ENOM,PHOM*
               PHIZ(14),KEY(14),DPHI(14)
COMMON /MEASUR/ QG(15), QE(15), Q3(15), QA(15), QS(15), Q6(15)
REAL PH1(15), KE, KP, KL
DO 10 I = 1,3
    FS(I) = 0.0
10 CONTINUE
DO 100 I = 1,NM1
    I1 = I + 1
    I2 = I + 2
    I3 = I + 3
    PHIL = DPHI(I)
C  =  CALCULATE DIFFERENTIAL SPRING ROTATION
    DPHI(I) = PH1(I) - PH1(I1)
    IF (KEY(I) .EQ. 3) GO TO 75
C  =  CHECK FOR JOINT SPRING FAILURE
    IF (ABS(DPHI(I)) .GT. PHF) 20,15,15
15 KEY(I) = 3
    GO TO 75
20 IF (DPHI(I) .NE. 0.0) GO TO 25
    SGN = 1.0
    GO TO 30
25 SGN = ABS(DPHI(I))/DPHI(I)
30 AOPHI = ABS(DPHI(I))
C  =  CHECK FOR DECREASING SPRING ROTATION
    IF (AOPHI .GT. PHIL) GO TO 60
    IF (KEY(I) .EQ. 3) 35,65,35
35 KEY(I) = 1
    GO TO 75
40 IF (AOPHI .GT. PHIL) GO TO 50
    SGIN = 1.0
    GO TO 70
50 PHIL = ENOM + EMOM/KE
55 PHIZ(I) = PHIL - SGN*(PHI(U + PHIS))
    GO TO 65
60 IF (KEY(I) .EQ. 1) KEY(I) = 2
65 DOPHI = DPHI(I) - PHIZ(I)
    AOPHI = ABS(DOPHI)
    IF (DOPHI .NE. 0.0) GO TO 70
    SGN = 1.0
    GO TO 71
70 SGN = AOPHI/DOPHI
C  =  FIND RANGE OF SPRING DEFORMATION, AND ADJUST IF NECESSARY
71 IF (AOPHI .LT. PHIF) 72,72,15
72 IF (AOPHI .LT. PHIP) 73,73,90
73 IF (AOPHI .LT. PHIE) 74,74,85
74 IF (AOPHI .LT. PHIS) 75,75,80
C  =  FIND FORCE (MOMENT) DUE TO DEFORMED SPRING
75 FORCE = 0.0
    GO TO 95
80 FORCE = KE*SGN*(AOPHI - PHIS)
    GO TO 95
85 FORCE = SGN*(EMOM + KP*(AOPHI - PHIF))
    GO TO 95
90 FORCE = SGN*(EMOM + PHOM + KP*(AOPHI - PHIP))
C  =  ARRANGE SPRING FORCE INTO GENERALIZED FORCE MATRIX
95 FS(I,P2) = FS(I,P2) + FORCE
    FS(I,P3) = FORCE
    J6(I) = FORCE
100 CONTINUE
RETURN
END

78
SUBROUTINE QEMTRX (PH)
COMMON /MEMBER/ M(15), P(15), L(15), 10(15), U(15), X(15)
COMMON /ENDPT/ XI(15), YI(15), XT(15), YT(15)
COMMON /MATRIX/ D(17,18), E(17), FS(17), QE(17), QF(17)
COMMON /CONF/ N, NP1, NP2, NM1, NP3, NP4, INDEX, DT, ET, ER, PI
COMMON /IMP/ CT, CM(50), XPT(50), YPT(50), NPTS, NPT, XF, YF,
* CF, FX, FY
REAL PHI(15), L
MARK = 0
C * FIND BARRIER SEGMENT IMPACT FORCE IS APPLIED TO
DO 20 J = 1,N
IF (XI(J)*GT.XF) GO TO 20
I = J
IF (XT(J)*GT.XF) GO TO 25
20 CONTINUE
WRITE (6,600) XF
MARK = 10
GO TO 100
25 TANPHI = TAN(PHI(I))
C * CALCULATE EACH ROW OF THE QE MATRIX
QE(1) = -FY*TANPHI
QE(2) = FY.
IF (I.EQ.1) GO TO 55
41 IM1 = I - 1
DO 50 J = 1,IM1
4J P2 = J + 2
QE(JP2) = FY*XPI(J)*(COS(PHI(J)) + TANPHI*SIN(PHI(J)))
50 CONTINUE
55 IP2 = I + 2
QE(IP2) = FY*(XP=XI(J))/(COS(PHI(J))**2)
IP3 = I + 3
DO 70 J = IP3, NP2
QE(J) = 0.0
70 CONTINUE
100 RETURN
600 FORMAT (*)
+ 15X 'COULD BE FOUND FOR XF = ' ,F10.3)
END
SUBROUTINE QFTRX (PHI, PHI(0))
COMM /MEMBER/ M(15), P(15), L(15), I(15), U(15), (15)
COMM /MATRIX/ Q(17,18), E(17), FS(17), QE(17), GF(17)
COMM /RCTN/ FX(15), FY(15)
COMM /CGRPS/ XO(15), YO(15), X00(15), Y00(15)
COMM /CONST/ NP1, NP2, NM1, NPROT, MARK, INDEX, ET, ER, P,
REAL QF(17), QFR(17), RO(15), PHI(15), PHID(15)
REAL M, L, IO
C = FIND RESULTANT TRANSLATIONAL VELOCITY FOR EACH BARRIER SEGMENT
DO 40 I = 1,N
RO(I) = (XO(I)**2 + YO(I)**2)**0.5
IF (RO(I).NE.0.0) GO TO 10
FFX(I) = 0.0
FFY(I) = 0.0
GO TO 40
C = DETERMINE FRICTION FORCES IN X- AND Y- DIRECTIONS
10 FFX(I) = -U(I)/RO(I)*XD(I)
IF (RO(I).GE.ET) GO TO 30
FFX(I) = FFX(I)*ABS(SIN(PHID(I)/(2.*ER)))
30 FFY(I) = -U(I)/RO(I)*YD(I)
IF (RO(I).GE.ET) GO TO 40
FFY(I) = FFY(I)*ABS(SIN(PHID(I)/(2.*ER)))
40 CONTINUE
C = CALCULATE THE GENERALIZED FORCES DUE TO TRANSLATIONAL FRICTION FORCES
SUMI = 0.0
SUM2 = 0.0
DO 50 I = 1,N
SUMI = SUMI + FFX(I)
SUM2 = SUM2 + FFY(I)
50 CONTINUE
QF(I) = SUMI
QF(2) = SUM2
DO 80 K = 1,N
KP1 = K + 1
KP2 = K + 2
QF(KP2) = -PHI(K)*SIN(PHID(K)) - FFY(K)*COS(PHID(K))
IF (K.EQ.0) GO TO 80
SUMI = 0.0
SUM2 = 0.0
DO 70 I = KP1,N
SUMI = SUMI + FFX(I)
SUM2 = SUM2 + FFY(I)
70 CONTINUE
QF(KP2) = QF(KP2) - L(K)*(SUMI*SIN(PHID(K)) - SUM2*COS(PHID(K)))
80 CONTINUE
C = EVALUATE FRICTION MOMENT DUE TO ROTATION OF SEGMENT
DO 90 K = 1,N
KP2 = K + 2
QFR(KP2) = PHID(K)*U(K)*L(K)/4.
IF (PHID(K).EQ.0.0) GO TO 90
QFR(KP2) = QFR(KP2)/ABS(PHID(K))
IF (ABS(PHID(K)).GE.ER) GO TO 90
QFR(KP2) = QFR(KP2)*ABS(SIN(PHID(K)/(2.*ER)))
90 CONTINUE
C = SUM TRANSLATIONAL AND ROTATIONAL GENERALIZED FORCES
DO 100 K = 1,N
QF(K) = QF(K) + QFR(K)
100 CONTINUE
RETURN
END
SUBROUTINE ADD
COMM /MATRIX/ Q(17,18), E(17), FS(17), QE(17), GF(17)
COMM /CGRPS/ XO(15), YO(15), X00(15), Y00(15)
COMM /CONST/ NP1, NP2, NM1, NPROT, MARK, INDEX, ET, ER, P,
REAL RMS(17)
EQUIVALENCE (RMS(1), E(1))
DO 20 I = 1,N
RMS(I) = E(I) + FS(I) + QE(I) + GF(I)
20 CONTINUE
RETURN
END
SUBROUTINE GAUSS(X)
COMMON /MATRIX/ A(17,18), C(17)
COMMON /CONST/ NM2,NM1,N,NM3,NPROT,MARK,INDEX,OT,ET,EP,P1
DIMENSION X(17)
DO 5 I = 1, N
A(I,NP1) = C(I)
5 CONTINUE
DO 30 K = 1,NM1
KP1 = K + 1
IF (A(K,KP1)*.NE.0.0) GO TO 10
10 IF (A(KP1,KP1)*.NE.0.0) GO TO 20
IF (KP1.EQ.N) GO TO 125
KP1 = KP1 + 1
GO TO 15
20 DO 30 J = K,NP1
STOREA = A(K,J)
A(K,J) = A(KP1,J)
A(KP1,J) = STOREA
30 CONTINUE
40 B = A(K,K)
DO 50 J = K,NP1
A(K,J) = A(K,J)/B
50 CONTINUE
DO 80 I = KP1,N
B = A(I,I)
DO 80 J = K,NP1
A(I,J) = A(I,J) - B*A(K,J)
80 CONTINUE
X(N) = A(N,NP1)/A(N,N)
DO 110 L = 1,NM1
K = N - L
X(K) = A(K,NP1)
KP1 = K + 1
DO 110 J = KP1,N
X(K) = X(K) - A(K,J)*X(J)
110 CONTINUE
INDEX = 2
RETURN
125 INDEX = 1
WRITE (6,600)
600 FORMAT ('**-10X;*** THE ACCELERATIONS COULD NOT BE SOLVED FOR',
+ '*** / 11X,*** DUE TO A SINGULARITY IN THE J MATRIX ***',)
RETURN
END

SUBROUTINE ACCEL (PHI,PHID,QOD)
COMMON /MEMBER/ X(15), P(15), L(15), M(15), U(15), A(15)
COMMON /GPROP/ XOD(15), YOD(15), XDD(15), YDD(15)
COMMON /CONST/ NM1,NP2,NM1,NPROT,MARK,INDEX,OT,ET,EP,P1
REAL PHI(15), PHID(15), QOD(17)
REAL L
DO 50 I = 1, N
JP2 = I + 2
XDD(I) = QOD(I) - P(I)*SIN(PHI(I)) - QOD(JP2) + CGS(PHI(I))*
+ PHID(I)**2)
YDD(I) = QOD(I) - P(I)*COS(PHI(I)) - QOD(JP2) - SIN(PHI(I))*
+ PHID(I)**2)
IF (I.EQ.1) GO TO 50
IM1 = I - 1
DO 45 J = 1,IM1
JP2 = J + 2
XDD(I) = XDD(I) - L(J)*SIN(PHI(J)) - QOD(JP2) + COS(PHI(J))*
+ PHID(J)**2)
YDD(I) = YDD(I) - L(J)*COS(PHI(J)) - QOD(JP2) - SIN(PHI(J))*
+ PHID(J)**2)
45 CONTINUE
50 CONTINUE
RETURN
END
SUBROUTINE ENOPC (PHI)
COMMON /MEMBER/ M(15), P(15), L(15), 10(15), U(15), X(15)
COMMON /SPRING/ PHS, PHI, PHP, PM, KE, KP, KL, ECMO, PMCM
+  PHI(14), KEY(14), OPHI(14)
COMMON /IMPACT/ TMPT(50), XPT(50), FPT(50), NPTS, IPT, XF, I=0&4
+ CF, FX, FY
COMMON /FRCTN/ FFX(15), FFFY(15)
COMMON /MEMFC/ Q1(15), Q2(15), Q3(15), Q4(15), QS(15), Q6(15)
COMMON /CGRP/ X0(15), Y0(15), XOD(15), YOD(15)
COMMON /CONST/ N, NP1, NP2, NMO, NPROT, MARK, INDEX, OT, ET, ER, P
REAL KH, KP, KL, M
DO 110 I = 1, N
IM1 = I - 1
IF (IM1 40, 40, 30
30 QI(1) = -QI(1) * COS(DPHI(1M1)) + QS(1) * SIN(DPHI(1M1))
QJ(1) = -QJ(1) * SIN(DPHI(1M1)) - QS(1) * COS(DPHI(1M1))
Q(1) = M(1) * XDD(1) + FFX(1) - Q2(1)
QA(1) = M(1) * XDD(1) + FFX(1) - Q1(1)
IF (I=IMBAR) 60, 50, 60
50 Q4(1) = Q4(1) - FY * SIN(PHI(1))
QS(1) = QS(1) - FY * COS(PHI(1))
60 CONTINUE
IF (IM1 110, 110, 70
70 Q3(1) = -Q6(1M1)
110 CONTINUE
RETURN
END

SUBROUTINE OUTPUT (TIME, PHI)
COMMON /TITLE/ HEAD1, HEAD2
COMMON /ENOPT/ X1(15), Y1(15), XT(15), YT(15)
COMMON /ALPHAS/ A0D(17), AZD(17), QOD(17)
COMMON /MEMFC/ Q1(15), Q2(15), Q3(15), Q4(15), QS(15), Q6(15)
COMMON /CGRP/ X0(15), Y0(15), XOD(15), YOD(15)
COMMON /CONST/ N, NP1, NP2, NMO, NPROT, MARK, INDEX, OT, ET, ER, P
CHARACTER*80 HEAD1, HEAD2
REAL PHI(15), PHID(15)
EQUIVALENCE (QOD(1J), PHID(1))
WRITE (6,060) TIME, HEAD1, HEAD2
WRITE (6,060)
DO 20 J = 1, N
WRITE (6,060) J, XI(J), Y1(J), XT(J), YT(J), PHI(J), XDD(J),
+ YDD(J), PH100(J)
20 CONTINUE
WRITE (6,060)
DO 60 J = 1, N
WRITE (6,060) J, Q1(J), Q2(J), Q3(J), Q4(J), QS(J), Q6(J)
60 CONTINUE
RETURN
600 FORMAT ('**TIME = ',1X,F10.4, ' ****',1X, 5X, A80 / 42X, 42D)
510 FORMAT ('***T40.** END POINT LOCATION** T104. CENTER OF MASS** / T11.
+ MEMBER** T32. INITIAL END** T56. TERMINAL END** T105. ACCELERATION**
+ T94. XDD. T109. YDD. T123. PH100.** /)
420 FORMAT ('**Q0.** 12.10X.4(F7.2,5X).4F4.2,5X)' JX. J5. X. 50.)
450 FORMAT ('**T4.** 12.10X.4(F7.2,5X).4F4.2,5X)' JX. J5. X. 50.)
460 FORMAT ('**T4.** 12.10X.4(F7.2,5X).4F4.2,5X)' JX. J5. X. 50.)
DESCRIPTION OF INPUT TO THE COMPUTER PROGRAM

First Card, Format (A80)

<table>
<thead>
<tr>
<th>Col. No.</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-80</td>
<td>HEAD1</td>
<td>Alphanumeric information for identification, printed on each output page</td>
</tr>
</tbody>
</table>

Second Card, Format (A80)

<table>
<thead>
<tr>
<th>Col. No.</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-80</td>
<td>HEAD2</td>
<td>Additional information continued from card one</td>
</tr>
</tbody>
</table>

Third Card, Format (2I5,3F10.2)

<table>
<thead>
<tr>
<th>Col. No.</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>N</td>
<td>Number of barrier segments*</td>
</tr>
<tr>
<td>6-10</td>
<td>NPRDT</td>
<td>Output print interval</td>
</tr>
<tr>
<td>11-20</td>
<td>DT</td>
<td>Time integration interval</td>
</tr>
<tr>
<td>21-30</td>
<td>ET</td>
<td>Translational velocity check</td>
</tr>
<tr>
<td>31-40</td>
<td>ER</td>
<td>Rotational velocity check</td>
</tr>
</tbody>
</table>

*Must be 15 or less.
### Properties of Barrier Segments

<table>
<thead>
<tr>
<th>Col. No.</th>
<th>Program</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>M(I)</td>
<td></td>
<td>Mass of segment I (lb sec^2/ft)</td>
</tr>
<tr>
<td>11-20</td>
<td>L(I)</td>
<td></td>
<td>Length of segment I (ft)</td>
</tr>
<tr>
<td>21-30</td>
<td>P(I)</td>
<td></td>
<td>Distance from reference end to center of mass for segment I (ft)</td>
</tr>
<tr>
<td>31-40</td>
<td>IO(I)</td>
<td></td>
<td>Mass moment of inertia about center of segment I (ft-lb-sec^2)</td>
</tr>
<tr>
<td>41-50</td>
<td>U(I)</td>
<td></td>
<td>Friction coefficient for segment I</td>
</tr>
</tbody>
</table>

There are N cards in this series.

### Joint Spring Parameters

<table>
<thead>
<tr>
<th>Card 1 Col. No.</th>
<th>Program</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>PHIS</td>
<td></td>
<td>Limit of slack rotation in joint spring (deg)</td>
</tr>
<tr>
<td>11-20</td>
<td>PHIE</td>
<td></td>
<td>Limit of elastic rotation in joint spring (deg)</td>
</tr>
<tr>
<td>21-30</td>
<td>PHIP</td>
<td></td>
<td>Limit of plastic rotation in joint spring (deg)</td>
</tr>
<tr>
<td>31-40</td>
<td>PHIF</td>
<td></td>
<td>Rotation in joint spring at failure (deg)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card 2 Col. No.</th>
<th>Program</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>KE</td>
<td></td>
<td>Elastic spring stiffness (ft-lb/deg)</td>
</tr>
<tr>
<td>11-20</td>
<td>KP</td>
<td></td>
<td>Plastic spring stiffness (ft-lb/deg)</td>
</tr>
<tr>
<td>21-30</td>
<td>KL</td>
<td></td>
<td>Lock-up spring stiffness (ft-lb/deg)</td>
</tr>
</tbody>
</table>
Sixth Card Set, Format (8F10.2)

Initial Position of Barrier

<table>
<thead>
<tr>
<th>Card 1</th>
<th>Program Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>XRO</td>
<td>Global X-position of initial end of system (ft)</td>
</tr>
<tr>
<td>11-20</td>
<td>YRO</td>
<td>Global Y-position of initial end of system (ft)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Card 2</th>
<th>Program Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>PHIO(1)</td>
<td>Initial rotation of segment 1 (deg)</td>
</tr>
<tr>
<td>11-20</td>
<td>PHIO(2)</td>
<td>Initial rotation of segment 2 (deg)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Input each of the N initial rotations; use additional cards as necessary.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coordinate orientation and sign convention shown here:</td>
</tr>
</tbody>
</table>

![Coordinate orientation and sign convention diagram]
Seventh Card Set

Impact Force on Barrier

Format (I5,5X,2F10.2)

<table>
<thead>
<tr>
<th>Card 1</th>
<th>Program Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>NPTS</td>
<td>Number of points in force input</td>
</tr>
<tr>
<td>5-10</td>
<td>Blank</td>
<td></td>
</tr>
<tr>
<td>11-20</td>
<td>PTIMP</td>
<td>Distance from reference end of barrier to XPT(1) = 0.0 (ft)</td>
</tr>
<tr>
<td>21-30</td>
<td>CF</td>
<td>Coefficient relating longitudinal to lateral force components</td>
</tr>
</tbody>
</table>

Format (6F10.2)

<table>
<thead>
<tr>
<th>Card 2</th>
<th>Program Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>TMPT(1)</td>
<td>Time at value of FPT(1) (sec)</td>
</tr>
<tr>
<td>11-20</td>
<td>XPT(1)</td>
<td>X-coordinate of location of FPT(1) (ft)</td>
</tr>
<tr>
<td>21-30</td>
<td>FPT(1)</td>
<td>Force perpendicular to barrier segment (lb)</td>
</tr>
<tr>
<td>31-40</td>
<td>TMPT(2)</td>
<td>Continue for second set of points</td>
</tr>
<tr>
<td>41-50</td>
<td>XPT(2)</td>
<td></td>
</tr>
<tr>
<td>51-60</td>
<td>FPT(2)</td>
<td></td>
</tr>
</tbody>
</table>

This same format is followed for the remaining sets of TMPT(I), XPT(I), FPT(I), punching two sets per card.

Suggested values for the impact force, time of application, and location on the barrier are given in the following table for two standardized crash tests. This input was used throughout the parameter evaluation of this research, and gives favorable comparisons with actual crash test results. (See results of test 2 for additional details.)
Standardized Force Input

4500 lb Vehicle, 60 mph, 15° Encroachment

<table>
<thead>
<tr>
<th>TIME (sec)</th>
<th>FORCE (lb)</th>
<th>DISTANCE FROM IMPACT (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.03</td>
<td>21100.</td>
<td>2.45</td>
</tr>
<tr>
<td>0.05</td>
<td>30800.</td>
<td>4.03</td>
</tr>
<tr>
<td>0.06</td>
<td>33600.</td>
<td>4.80</td>
</tr>
<tr>
<td>0.07</td>
<td>35200.</td>
<td>5.56</td>
</tr>
<tr>
<td>0.08</td>
<td>35600.</td>
<td>6.30</td>
</tr>
<tr>
<td>0.09</td>
<td>35000.</td>
<td>7.03</td>
</tr>
<tr>
<td>0.10</td>
<td>33400.</td>
<td>7.74</td>
</tr>
<tr>
<td>0.13</td>
<td>25100.</td>
<td>9.83</td>
</tr>
<tr>
<td>0.17</td>
<td>11400.</td>
<td>12.55</td>
</tr>
<tr>
<td>0.20</td>
<td>4500.</td>
<td>14.58</td>
</tr>
<tr>
<td>0.21</td>
<td>2800.</td>
<td>15.26</td>
</tr>
<tr>
<td>0.22</td>
<td>1500.</td>
<td>15.97</td>
</tr>
<tr>
<td>0.23</td>
<td>600.</td>
<td>16.62</td>
</tr>
<tr>
<td>0.24</td>
<td>0.0</td>
<td>17.30</td>
</tr>
</tbody>
</table>

4500 lb Vehicle, 60 mph, 25° Encroachment

<table>
<thead>
<tr>
<th>TIME (sec)</th>
<th>FORCE (lb)</th>
<th>DISTANCE FROM IMPACT (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.01</td>
<td>0.0</td>
<td>0.85</td>
</tr>
<tr>
<td>0.02</td>
<td>5560.</td>
<td>1.70</td>
</tr>
<tr>
<td>0.05</td>
<td>60400.</td>
<td>4.21</td>
</tr>
<tr>
<td>0.06</td>
<td>72800.</td>
<td>5.02</td>
</tr>
<tr>
<td>0.07</td>
<td>72800.</td>
<td>5.83</td>
</tr>
<tr>
<td>0.08</td>
<td>77600.</td>
<td>6.62</td>
</tr>
<tr>
<td>0.09</td>
<td>70200.</td>
<td>7.41</td>
</tr>
<tr>
<td>0.13</td>
<td>18000.</td>
<td>10.47</td>
</tr>
<tr>
<td>0.14</td>
<td>8390.</td>
<td>11.22</td>
</tr>
<tr>
<td>0.15</td>
<td>3170.</td>
<td>11.97</td>
</tr>
<tr>
<td>0.16</td>
<td>1510.</td>
<td>12.72</td>
</tr>
<tr>
<td>0.17</td>
<td>2600.</td>
<td>13.46</td>
</tr>
<tr>
<td>0.19</td>
<td>8400.</td>
<td>14.96</td>
</tr>
<tr>
<td>0.20</td>
<td>10800.</td>
<td>15.71</td>
</tr>
<tr>
<td>0.21</td>
<td>11800.</td>
<td>16.46</td>
</tr>
<tr>
<td>0.23</td>
<td>8730.</td>
<td>17.97</td>
</tr>
<tr>
<td>0.25</td>
<td>1490.</td>
<td>18.72</td>
</tr>
<tr>
<td>0.26</td>
<td>0.0</td>
<td>19.47</td>
</tr>
</tbody>
</table>
BARRIERS IN CONSTRUCTION ZONES

APPENDIX D

Strength of Portable Median Barrier Connections

Prepared for
Contract DOT-FH-11-9458
Office of Research
Federal Highway Administration
U. S. Department of Transportation

by

W. Lynn Beason
Assistant Research Engineer

Texas A&M Research Foundation
Texas Transportation Institute
The Texas A&M University System
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Figure 19. Portable Construction Zone Barrier.
Table 11. Assumed Material Strengths.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Compressive Strength (ksi)</th>
<th>Yield Strength in Tension (ksi)</th>
<th>Yield Strength in Shear (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>$f'_c = 3.0$</td>
<td>---</td>
<td>$\tau_{\text{ult}} = 0.3$</td>
</tr>
<tr>
<td>Rebar Bolts, and welds</td>
<td>---</td>
<td>$\sigma_y = 36$</td>
<td>$\tau_y = 20.8$</td>
</tr>
<tr>
<td>Structural Steel</td>
<td>---</td>
<td>$\sigma_y = 36$</td>
<td>$\tau_y = 20.8$</td>
</tr>
<tr>
<td>Wire Rope and Cable</td>
<td>---</td>
<td>$\sigma_{\text{ult}} = 91.7^2$</td>
<td>$\tau_{\text{ult}} = 52.9^2$</td>
</tr>
<tr>
<td>Structural Steel Tube</td>
<td>---</td>
<td>$\sigma_y = 46$</td>
<td>$\tau_y = 26.6$</td>
</tr>
</tbody>
</table>

1 all shear strengths except for concrete are based on energy of distortion theory, i.e. $\tau_y = \sigma_y / \sqrt{3}$

2 strengths based on gross cross-sectional area
Figure 20. Welsbach Interlock (New Jersey).
Figure 21. Forces on Interlock Due to Tension in Connection.

Figure 22. Forces on Interlock Due to Shear in Connection.
The New York I-Lock connection is shown in Figure 25. The connection between barrier sections is accomplished by inserting a specially fabricated steel key into slotted steel tubes which are cast in the barrier ends.

**TENSILE CAPACITY**

The tensile capacity, $F_T$, of this connection is controlled by the strength of the I-lock loaded as shown in Figure 26, or the capacity of the structural tube loaded as shown in Figure 27. The strength of the I-lock will be checked first.

**SHEAR CAPACITY OF FILET WELDS**

If the yield strength of the weld shown in Figure 26 is assumed to be 34.6 ksi, the tensile strength of the connection is given as follows:

$$F_T = 2(20 \text{ in.})(.707)(5/16 \text{ in.})(34.6 \text{ ksi}),$$

$$F_T = 305.8 \text{ k.}$$

**SHEAR STRENGTH AT POINT B**

If the yield strength of the I-lock at point B in shear is assumed to be 20.8 ksi (ref. Fig. 26), the tensile strength of the connection is given as follows:

$$F_T = 2(1/2 \text{ in.})(20 \text{ in.})(20.8 \text{ ksi}),$$

$$F_T = 416 \text{ k.}$$

**TENSILE STRENGTH AT POINT A**

If the yield strength of the I-lock in tension is assumed to be 36 ksi (ref. Fig. 26), the tensile strength of the connection is given as follows:

$$F_T = 1/2 \text{ in.}(20. \text{ in.})(36 \text{ ksi}),$$

$$F_T = 360 \text{ ksi.}$$

**FLEXURAL STRENGTH OF STRUCTURAL TUBE AT POINT A**

If the yield strength of the structural tube is assumed to be 46 ksi, the maximum plastic moment, $M_{pl}$, at point A on the tube (ref. Fig. 27) is given as follows:

$$M_{pl} = 46 \text{ ksi}(1/4 \text{ in.})(20 \text{ in.})(1/4 \text{ in.}),$$

$$M_{pl} = 57.5 \text{ in.-k.}$$

The tensile capacity of the connection is then calculated as follows:

$$F_T = 2(57.5 \text{ in.-k.})(1.25 \text{ in.}),$$

$$F_T = 92 \text{ k.}$$
Figure 25. I-Lock (New York).
(a) Side View of I-Lock  

(b) I-Lock Cross-Section

Figure 26. Forces in I-Lock Due to Tension in Connection.

Figure 27. Forces on Structural Tube When Connection is in Tension.
SHEAR CAPACITY OF STRUCTURAL TUBE BELOW POINT A

If it is assumed that the yield strength of the tube in shear just below point A is 26.6 ksi (ref. Fig. 27), the tensile strength of the connection is given as follows:

\[ F_T = 2(20 \text{ in.})(1/2 \text{ in.})(26.6 \text{ ksi}), \]

\[ F_T = 532 \text{ k}. \]

The tensile capacity of this connection is thus calculated to be 92 k.

SHEAR CAPACITY

The shear strength, \( V \), of this connection is controlled by the shear strength of the I-lock loaded as shown in Figure 28. If the yield strength of the I-lock in shear is assumed to be 20.8 ksi, the shear strength of the connection is given as follows:

\[ V = 1/2 \text{ in.}(20 \text{ in.})(20.8 \text{ ksi}), \]

\[ V = 208 \text{ k}. \]

The shear capacity of connection is thus calculated to be 208 k.

BENDING CAPACITY

The bending capacity, \( M \), of this connection is controlled by the couple that develops between the tensile force in the I-lock and the compressive force in the concrete barrier face as shown in Figure 23. If it is assumed that the moment arm, \( d \), shown in Figure 23 is equal to 8 in., the bending capacity of this connection is given as follows:

\[ M = 92 \text{ k}(8 \text{ in.}), \]

\[ M = 736 \text{ in.-k or 61.3 ft-k}. \]

The bending capacity of this connection is thus calculated to be 61 ft-k.

TORSION CAPACITY

The torsion capacity, \( T \), of this connection is the result of shearing stresses in the web of the I-lock as shown in Figure 29. If it is assumed that the yield strength of the I-lock in shear is equal to 20.8 ksi, the torsion capacity of the connection is given as follows:

\[ T = 10 \text{ in.}(1/2 \text{ in.})(20.8 \text{ ksi})(10 \text{ in.}), \]

\[ T = 1040 \text{ in.-k or 86.7 ft-k}. \]

The torsion capacity of this connection is thus calculated to be 87 ft-k.
Figure 28. Forces on I-Lock Cross-Section When Connection is in Shear.

Figure 29. Shear Stress Distribution in I-Lock Web When Connection is in Torsion.
PIN AND REBAR (California)

The California pin and rebar connection is shown in Figure 30. Steel loops are cast in the ends of the barrier face so that loops in opposing ends of the barrier align as shown. The connection is accomplished by inserting a bolt through the loops and installing a nut and washer on the bolt end.

TENSION CAPACITY

The tension capacity, \( F_T \), of this connection is controlled by the strength of the steel loops loaded as shown in Figure 31 or the strength of the bolt loaded as shown in Figure 32. The strength of the steel loops will be addressed first.

TENSILE CAPACITY OF STEEL LOOPS

If it is assumed that the yield strength of the steel loops in tension is 60 ksi (ref. Fig. 31), the tensile strength of the connection is calculated as follows:

\[
F_T = 2 \cdot 2 \cdot (\pi) \left( \frac{3}{8}\text{ in.} \right)^2 \cdot 60 \text{ ksi},
\]

\[
F_T = 106 \text{ k.}
\]

SHEAR STRENGTH OF BOLT

If the shear strength of the bolt is assumed to be 34.7 ksi (ref Fig. 32), the tensile capacity of the connection is given as follows:

\[
F_T = 2 \cdot (\pi) \left( \frac{5}{8}\text{ in.} \right)^2 \cdot 34.7 \text{ ksi},
\]

\[
F_T = 85.2 \text{ k.}
\]

BENDING STRENGTH OF BOLT

The bending strength of the bolt in this connection is not at issue because the nut on the bottom of the bolt prevents failure of the bolt in this mode.

The tensile capacity of this connection is thus calculated to be 85 k.

SHEAR CAPACITY

The shear capacity, \( V \), of this connection is controlled by the same mechanism as the tension capacity. Therefore, the shear capacity is calculated to be 85 k.
Figure 30. Pin and Rebar (California).
Figure 31. Forces in Steel Loops Due to Tension in Connection.

Figure 32. Forces on Bolt Due to Tension in Connection.
BENDING CAPACITY

The bending capacity, M, of this connection is the result of the couple which develops between the tensile force in the steel loops and the compressive force in the extreme fibers of the barrier end as shown in Figure 23. If it is assumed that the moment arm, d, in Figure 23 is 8 in., the bending strength of the connection is given as follows:

\[ M = 85.2 \text{ k}(8 \text{ in.}), \]
\[ M = 681.6 \text{ in.-k} \text{ or } 56.8 \text{ ft-k}. \]

The bending capacity of the connection is thus calculated to be 57 ft-k.

TORSION CAPACITY

The torsion capacity, T, of this connection is the result of the couple which develops between the forces on the steel loops as shown in Figure 24. The moment arm, d, for this connection is 17 in. If it is assumed that this force is limited by the shear strength of the pin, the torsion capacity of the connection is given as follows:

\[ T = (85.2 \text{ k}/2)(17 \text{ in.}), \]
\[ T = 724.2 \text{ in.-k} \text{ or } 60.4 \text{ ft-k}. \]

The torsion capacity of this connection is thus calculated to be 60 ft-k.
The California corrugation and cable connection is shown in Figure 33. The connection is accomplished by post tensioning the corrugated barrier ends together as shown in Figure 33.

**TENSION CAPACITY**

The tension capacity, $F_T$, of this connection is controlled by the tensile strength of the wire rope loaded as shown in Figure 34. If it is assumed that the ultimate tensile strength of the wire rope is 91.7 (on the gross cross-section), the tensile strength of the connection is given as follows:

$$F_T = \pi (3/8 \text{ in.})^2 (91.7 \text{ ksi})$$

$$F_T = 40.5 \text{ k.}$$

The tensile capacity of the connection is thus calculated to be 41 k.

**SHEAR CAPACITY**

When this connection is subjected to shear, the tendency will be for the connection to open as shown in Figure 35. This results in a tensile force in the wire rope and a normal force between the barrier sections. Therefore, the shear capacity, $V$, of the connection is limited by one of two factors, the magnitude of the friction between the concrete barriers as shown in Figure 36, or the shear strength of the cable as shown in Figure 37.

**FRICTION BETWEEN BARRIERS.**

The maximum tensile force that the wire rope can develop was calculated above to be 40.5 k. If it is assumed that the coefficient of friction between the barrier sections is 0.70, the shear strength of the barrier is given as follows:

$$V = (0.7) (40.5 \text{ k})$$

$$V = 28.4 \text{ k.}$$

**SHEAR STRENGTH OF CABLE**

If it is assumed that the ultimate shear strength of the cable is 52.9 ksi on the gross area (ref. Fig. 37), the shear strength of the connection can be calculated as follows:

$$V = \pi (3/8 \text{ in.})^2 (52.9 \text{ ksi})$$

$$V = 23.4 \text{ k.}$$

The shear strength of the connection is thus calculated to be 23 k.
Figure 33. Corrugation and Cable (California).
Figure 34. Forces on Wire Rope When Connection is in Tension.

Figure 35. Connection in Shear.
Figure 36. Friction on Barrier Face When Connection is in Shear.

Figure 37. Forces on Cable When Connection is in Shear.
**BENDING CAPACITY**

The bending capacity, $M$, of this connection is the result of the couple which forms between the wire rope and the extreme fibers of the barrier segments as shown in Figure 23. The magnitude of the tensile force in the wire rope was previously calculated to be 40.5 k. If it is assumed that the moment arm, $d$, in Figure 23 is equal to 8 in., the bending capacity of the connection can be calculated as follows:

$$M = (40.5 \text{ k})(8 \text{ in.}),$$

$$M = 324.0 \text{ in.-k or 27.0 ft-k.}$$

Therefore, the bending capacity of this connection is calculated to be 27 ft-k.

**TORSION CAPACITY**

The torsion capacity, $T$, of this connection barrier is the result of the frictional shear forces on the barrier face as shown in Figure 38. The resultant shear force on the barrier face will be 28.4 k as previously calculated. If it is assumed that the moment arm associated with this resultant force is 8 in., the torsion capacity of the section is given as follows:

$$T = (28.4 \text{ k})(8 \text{ in.}),$$

$$T = 227.2 \text{ in.-k or 18.9 ft-k.}$$

The torsion capacity of this connection is thus calculated to be 19 ft-k.
Figure 38. Frictional Forces on Barrier Face When Connection is in Torsion.
The Texas lapped joint and bolt connection is shown in Figure 39. The ends of each barrier segment are specially fabricated so that they overlap in a vertical plane. The connection is accomplished by inserting and tightening a single 1 in. diameter steel bolt.

**TENSILE CAPACITY**

The tensile capacity, $F_T$, of this joint is controlled by the shear strength of the connecting bolt as shown in Figure 40. If the yield strength of the bolt in shear is assumed to be 34.6 ksi (ref. Fig. 40), the tensile strength of the connection is given as follows:

$$F_T = \pi (1/2 \text{ in.})^2 (34.6 \text{ ksi}),$$

$$F_T = 27.2 \text{ k.}$$

The tensile capacity of the joint is thus calculated to be 27 k.

**SHEAR CAPACITY**

The shear capacity, $V$, of this connection is controlled by either the tensile strength of the connecting bolt as shown in Figure 41 or the shearing strength of the failure plane as indicated in Figure 42.

**TENSILE STRENGTH OF BOLT**

If the yield strength of the bolt in tension is assumed to be 60 ksi, the shear strength of the connection is given as follows:

$$V = \pi (1/2 \text{ in.})^2 (60 \text{ ksi}),$$

$$V = 47.1 \text{ k.}$$

**SHEAR STRENGTH ACROSS FAILURE PLANE**

If failure of the barrier connection occurs along the failure plane indicated in Figure 42, a total of four bars of unknown diameter (assumed to be 3/8 in.), one steel plate with a 4 in. x 1/2 in. cross-section, and the concrete itself must fail in shear (ref. Fig. 39). If it is assumed that the yield strength of the steel bars in shear is 34.6 ksi, the yield strength of the steel plate in shear is 20.8 ksi, and the ultimate shear strength of the concrete is 110 psi, the shear strength of the connection is given as follows:

$$V = 4(\pi)(3/16 \text{ in.})^2 (34.6 \text{ ksi}) + (4 \text{ in.})(1/2 \text{ in.})(36 \text{ ksi})$$

$$+ (200 \text{ sq. in.})(.110 \text{ ksi}),$$

$$V = 109.3 \text{ k.}$$
Figure 39. Lapped Joint and Bolt (Texas).
Figure 40. Shear Force in Bolt When Connection is in Tension.

Figure 41. Tensile Force in Bolt When Connection is in Shear.
The shear strength of this connection is thus calculated to be 47 k.

**BENDING CAPACITY**

The bending capacity, $M$, of this connection is developed as a result of the couple which develops between the tensile force in the connecting bolt and the compressive force between the concrete barrier ends as shown in Figure 43. If the tensile strength of the bolt is taken to be 47.1 k as calculated earlier and the ultimate compressive strength of the concrete is taken as 0.85 (3000 ksi), the width, $w$, of the compressive zone shown in Figure 43 is given as follows:

$$w = \frac{47.1}{[(30 \text{ in.})(.85)(3 \text{ ksi})]}$$
$$w = .62 \text{ in.}$$

The value of moment arm, $d$, is then be calculated as follows:
$$d = 6 \text{ in.} - .62 \text{ in.}/2,$$
$$d = 5.7 \text{ in.}$$

The moment capacity of the connection is then given as follows:
$$M = 47.1 \text{ k}(5.7 \text{ in.}),$$
$$M = 268.5 \text{ in.-k} \text{ or } 22.4 \text{ ft-k}.$$  

The bending capacity of this connection is thus calculated to be 22 ft-k.

**TORSION CAPACITY**

The torsion capacity, $T$, of this section is controlled by the couple which develops between the tensile force in the bolt and the compressive force on the barrier as shown in Figure 44. If it is assumed that the moment arm, $d$, is equal to 6 in., the torsion capacity of the connection is calculated as follows:
$$T = 47.1 \text{ k}(6 \text{ in.}),$$
$$T = 282.6 \text{ in.-k} \text{ or } 23.6 \text{ ft-k}.$$  

The torsion capacity of the connection is thus calculated to be 24 ft-k.
Shear Plane (area = 200 sq. in.)

Figure 42. Shear Plane in Concrete When Connection is in Shear.

Figure 43. Forces on Barrier Face When Connection is in Bending.
Figure 44. Forces on Barrier When Connection is in Torsion.
PIN AND EYE BOLT (Minnesota)

The Minnesota pin and eye bolt connection is shown in Figure 45. Eye bolts are cast into the ends of the barrier segments so that the bolts in opposing ends of the barrier align as shown. The connection is completed by inserting a connection pin through the eye bolts.

TENSION CAPACITY

The tensile capacity, \( F_T \), of this connection is controlled by the strengths of the eye bolts or the strength of the pin. If moments are summed about point A in Figure 46 the following relationship between the forces in the eye bolts results:

\[
P_I = 1.25 P_0
\]

Therefore

\[
F_T = 2.25 P_0
\]

or

\[
F_T = 1.80 P_I
\]

STRENGTH OF THE EYE BOLTS

It is assumed that the strength of the eye bolt is controlled by the tensile strength of the shank as shown in Figure 47. If it is assumed that the yield strength of the eye bolt shank in tension is 36 ksi, the tensile strength of the connection is given as follows:

\[
F_T = 1.8(3/8 \text{ in.})^2(\pi)(.70)(36 \text{ ksi}),
\]

\[
F_T = 20.0 \text{ k.}
\]

SHEAR STRENGTH OF THE PIN

The maximum shear in the pin occurs just above point A (ref. Fig. 46). If it is assumed that the yield strength of the pin in shear is 34.6 ksi, the tensile strength of the connection is given as follows:

\[
F_T = 2.25 (34.6 \text{ ksi})(\pi)(5/8 \text{ in.})^2,
\]

\[
F_T = 95.5 \text{ k.}
\]

FLEXURAL STRENGTH OF THE PIN

The maximum moment in the pin occurs 2 in. above point A as shown in Figure 46. If it is assumed that the yield strength of the pin in tension is 60 ksi, the plastic moment capacity of the pin is given as follows:

\[
M_{pl} = 4/3(5/8 \text{ in.})^3(60 \text{ ksi}),
\]

\[
M_{pl} = 19.5 \text{ in.-k.}
\]
Figure 45. Pin and Eye Bolt (Minnesota).
\[ \sum M_A = 0 \]

\[ 2P_1 - 18P_1 + 20P_0 = 0 \]

\[ P_1 = 1.25P_0 \]

**Figure 46.** Forces on Pin When Connection is in Tension.

\[ 3/4'' \varnothing \]

**Figure 47.** Forces on Eye Bolt When Connection is in Tension.
The tensile strength of the connection can then be calculated as follows:
\[ F_T = 2.25 \times (19.5 \text{ in.-k}/2 \text{ in.}) \]
\[ F_T = 21.9 \text{ k} \]
The tensile strength of the connection is thus calculated to be 20 k.

**SHEAR CAPACITY**

The shear strength, \( V \), of this connection is controlled by either the strengths of the eye bolts loaded as shown in Figure 48, or the strength of the pin loaded essentially the same as shown in Figure 46.

**SHEAR STRENGTH OF THE EYE BOLT**

If the yield strength of the eye bolt in shear is assumed to be 20.8 ksi, the shear strength of the connection is given as follows:
\[ V = 1.8(20.8 \text{ ksi})(\pi)(3/8 \text{ in.})^2(.70) \]
\[ V = 11.6 \text{ k} \]

**STRENGTH OF PIN**

The shear and bending strengths of the pin are the same as calculated above in the tensile capacity section.

The shear strength of the connection is thus calculated to be 12.0 k.

**BENDING CAPACITY**

The bending capacity, \( M \), of this connection is controlled by the couple which develops between the tensile force in the eye bolt and the compression between the concrete barriers in contact as shown in Figure 23. If it is assumed that the moment arm, \( d \), shown in Figure 23 is 8 in., the moment capacity of the connection is calculated as follows:
\[ M = 20.0 \text{ k}(8 \text{ in.}) \]
\[ M = 160.0 \text{ in.-k or 13.3 ft-k} \]

The bending capacity of the connection is thus calculated to be 13 ft-k.

**TORSION CAPACITY**

The torsion capacity of this connection is the result of the couple which develops between the forces acting on the pin as shown in Figure 49. The following equilibrium equation can be developed by summing moments about point A in Figure 49.
\[ P_0 = P_I \]
Figure 48. Forces Acting on Eye Bolt When Connection is in Shear.

\[ \Sigma M_A = 0 \]
\[ 2P_I + 18P_I - 20P_0 = 0 \]
\[ P_I = P_0 \]

Figure 49. Forces Acting on Pin When Connection is in Torsion.
The forces are limited by either the strength of the eye bolt or the strength of the pin.

SHEAR STRENGTH OF EYE BOLT

If it is assumed that the yield strength of the eye bolts in shear is 20.8 ksi, the torsional capacity of the connection is given as follows:

\[ T = 20.8 \text{ ksi}(\pi)(3/8 \text{ in.})^2(0.70)(16 \text{ in.}), \]
\[ T = 102.9 \text{ in.-k} \text{ or } 8.6 \text{ ft-k}. \]

SHEAR STRENGTH OF PIN

If the yield strength of the pin in shear is assumed to be 34.6 ksi, the torsional capacity of the connection is given as follows:

\[ T = \pi(5/8 \text{ in.})^2(34.6 \text{ ksi})(16 \text{ in.}), \]
\[ T = 679.4 \text{ in.-k} \text{ or } 56.6 \text{ ft-k}. \]

FLEXURAL STRENGTH OF PIN

If the yield strength of the pin in tension is assumed to be 60 ksi, the plastic moment capacity is 19.5 in.-k as calculated earlier. The torsional capacity of the connection is calculated as follows:

\[ T = (19.5 \text{ in.-k}/2\text{in.})(16 \text{ in.}), \]
\[ T = 156.0 \text{ in.-k} \text{ or } 13.0 \text{ ft-k}. \]

The torsion capacity of the connection is thus calculated to be 9 ft-k.
PIN AND WIRE ROPE (Idaho)

The Idaho pin and wire rope connection is shown in Figure 50. Wire rope loops are cast into the ends of the barrier segments so that the loops in opposing ends of the barrier overlap as shown. The connection is completed by inserting a threaded steel pin through the loops and installing a nut and washer on the bottom end of the steel pin.

**TENSION CAPACITY**

The tensile capacity, $F_T$, of this connection is controlled by the strength of the pin and wire rope loaded as shown in Figure 51. If moments are summed about point A of the pin as shown in Figure 51, the following equilibrium equation results:

$$P_I = 1.25 P_o$$

Therefore

$$F_T = 2.25 P_o$$

or

$$F_T = 1.80 P_I$$

**TENSILE STRENGTH OF WIRE ROPE**

The wire rope loops are loaded in tension as shown in Figure 52. If it is assumed that the tensile strength of the wire rope is 91.7 ksi (on the gross cross-section), the tensile strength of the connection is given as follows:

$$F_T = 1.8(2)(91.7 \text{ ksi})(\pi)(1/4 \text{ in.})^2$$

$$F_T = 64.8 \text{ k.}$$

**SHEAR CAPACITY OF PIN**

If it is assumed that the yield strength of the pin in shear is 34.6 ksi, the tensile strength of the connection is given as follows:

$$F_T = (2.25)(34.6 \text{ ksi})(\pi)(1/2 \text{ in.})^2$$

$$F_T = 61.1 \text{ k.}$$

**BENDING CAPACITY OF PIN**

The bending strength of the pin is not a controlling factor for this connection because the pin is equipped with a nut and washer.

The tensile capacity of this connection is thus calculated to be 61 k.
Figure 50. Pin and Wire Rope (Idaho).
\[ \Sigma M_A = 0 \]

\[ 2P_I - 18P_I + 20P_O = 0 \]

\[ P_I = 1.25P_O \]

**Figure 51.** Forces on Pin When Connection is Tension.

**Figure 52.** Forces on Loops When Connection is Tension.
PIN AND REBAR (Georgia)

The Georgia pin and rebar connection is shown in Figure 54. Steel loops are cast in the ends of the concrete median barrier so that the loops in the opposing ends overlap as shown. The connection is completed by inserting a 7/8 in. diameter pin which is held in place with a nut and washer as shown in Figure 54.

TENSION CAPACITY

The tension capacity, \( F_T \), of this connection is controlled by the strength of the loops loaded as shown in Figure 56, or the strength of the pin loaded as shown in Figure 55. If moments are summed about point \( A \) in Figure 55 the following relationship between the forces on the pin results:

\[
P_I = 1.22 \, P_0
\]

therefore

\[
F_T = 2.22 \, P_0
\]

or

\[
F_T = 1.82 \, P_I
\]

The first set of calculations is concerned with the strength of the steel loops.

TENSILE STRENGTH OF LOOPS

Figure 56 presents the tensile loads acting on a typical steel loop. If it is assumed that the yield strength of the loop in shear is 60 ksi, the tensile strength of the connection is given as follows:

\[
F_T = 2(1.82)(\pi)(3/8 \text{ in.})^2(60 \text{ ksi}),
\]

\[
F_T = 96.5 \text{ k.}
\]

SHEAR CAPACITY OF PIN

If the yield strength of the pin in shear is assumed to be 34.7 ksi, the tensile capacity of the connection is given as follows:

\[
F_T = 2.22 \, (\pi)(7/16 \text{ in.})^2(34.7 \text{ ksi}),
\]

\[
F_{FT} = 46.3 \text{ k.}
\]

BENDING STRENGTH OF PIN

The bending strength of the pin is not a controlling mechanism for this connection because the pin is securely fastened in place with a nut.

The tensile capacity of this connection is thus calculated to be 46 k.
Figure 54. Pin and Rebar (Georgia).
SHEAR CAPACITY

The shear capacity, $V$, of the connection is controlled by the same mechanism as the tension capacity. Therefore the shear capacity of the connection is 46 k.

BENDING CAPACITY

The bending capacity, $M$, of this connection is developed as a result of the couple between the tensile force in the hooks and the compressive force in the extreme fibers of the concrete barriers in contact as shown in Figure 23. If the magnitude of the tensile force is taken to be $41.3 \text{ k}$ as calculated above and the moment arm, $d$, in Figure 23 is assumed to be 8 in., the bending capacity of the connection is given as follows:

$$M = 46.3 \text{ k (8 in.)},$$
$$M = 370.4 \text{ in.-k or } 30.9 \text{ k-ft}.$$

The bending capacity of this connection is thus calculated to be 31 ft-k.

TORSION CAPACITY

The torsion capacity, $T$, of this connection is the result of the couple which develops between the forces between the pin and the loops as shown in Figure 57. If moments are summed about point A in Figure 57, the following relationship between the forces results:

$$P_0 = P_1$$

The magnitudes of the forces between the pin and the hooks is controlled by either the strength of the hooks or the strength of the pin.

TENSILE STRENGTH OF HOOKS

Figure 57 presents the tensile forces acting on a steel loop. If it is assumed that the yield strength of the loop in tension is 60 ksi, the torsion capacity of the section is given as follows:

$$T = 2 \pi \left(\frac{7}{16} \text{ in.}\right)^2 \left(60 \text{ ksi}\right)\left(18 \text{ in.}\right),$$
$$T = 1298.9 \text{ in.-k or } 108.2 \text{ ft-k}.$$

SHEAR STRENGTH OF PIN

If the yield strength of the pin in shear is assumed to be 34.7 ksi, the torsion capacity of the connection is given as follows:
\[ \sum M_A = 0 \]

\[ 2P_1 + 18P_1 - 20P_0 = 0 \]

\[ P_1 = P_0 \]

Figure 57. Forces on Pin When Connection is in Torsion.
\[ T = \pi \left(\frac{7}{16} \text{ in.}\right)^2 (34.7 \text{ ksi})(18 \text{ in.}), \]
\[ T = 375.6 \text{ in.-k} \text{ or } 31.3 \text{ ft-k}. \]

The torsion capacity of the connection is thus calculated to be 31 ft-k.
The Texas Dowel connection is shown in Figure 58. Three steel dowels are cast into one end of the barrier section and three grooves are cast into the other end of the barrier section. The connection is made by inserting the dowels on one end of a barrier section into the grooves on the end of another barrier section. When this connection is used in a permanent installation grout is pumped into the grooves and into the interface area between the barrier sections; however, grout is not used in a temporary installation.

**Tensile Capacity**

The tensile capacity, $F_T$, of this connection is zero because grout is not used in a temporary installation.

**Shear Capacity**

The shear capacity, $V$, of this connection is controlled by the shear strength of the dowels as shown in Figure 59, or the bending strength of the dowels as shown in Figure 60.

**Shear Strength of Dowels**

If it is assumed that the yield strength of the steel dowels in shear is 34.6 ksi, the shear strength of the connection is given as follows:

$$V = 3\pi (1/2 \text{ in.})^2(34.6 \text{ ksi}),$$

$$V = 81.5 \text{ k.}$$

**Bending Strength of Dowels**

If it is assumed that the yield strength of the steel dowels in tension is 60 ksi, the plastic moment capacity of the dowel is calculated as follows:

$$M_{pl} = \frac{4}{3}(1/2 \text{ in.})^3(60 \text{ ksi}),$$

$$M_{pl} = 10.0 \text{ in.-k.}$$

If it is assumed that the moment arm, $d$, shown in Figure 60 is equal to 1 in., the shear strength of the connection is calculated as follows:

$$V = 3(2)(10 \text{ in.-k}/1 \text{ in.}),$$

$$V = 60.0 \text{ k.}$$

The shear capacity of this section is thus calculated to be 60 k.
Figure 58. Dowel (Texas).
Figure 59. Shear Forces on Dowel When Connection is in Shear.

Figure 60. Dowels in Bending When Connection is in Shear.
**BENDING CAPACITY**

The bending capacity, $M$, of this connection is zero because grout is not used in temporary connections.

**TORSION CAPACITY**

It is assumed that the torsion capacity, $T$, of this connection is the result of the couple which develops between the two outer dowels as shown in Figure 61. It was seen earlier that the maximum shear force in the dowel, is limited by the bending strength of the dowels. Assuming that the plastic moment capacity of a dowel is 10.0 in.-k as calculated earlier, the torsion capacity of the connection is given as follows:

$$T = 2(10 \text{ in.-k/1 in.})(22 \text{ in.}),$$

$$T = 440.0 \text{ in.-k} \text{ or } 36.7 \text{ ft-k}.$$  
The torsion capacity of the section is thus calculated to be 37 ft-k.
Figure 61. Forces on Dowels When Connection is in Torsion.
TONGUE AND GROOVE (Oregon)

The Oregon tongue and groove connection is shown in Figure 62. Two protrusions are cast on the face of one end of the barrier and two grooves are cast on the other end of the barrier. The connection is accomplished by inserting the protrusions on one end of the barrier into the groove on the other end of the barrier.

TENSILE CAPACITY

The tensile capacity, $F_T$, of this connection is zero because there is no positive attachment between barrier sections.

SHEAR CAPACITY

The shear capacity, $V$, of this connection is controlled by the force required to shear the concrete protrusions from the end of a barrier as shown in Figure 63. The total area of the concrete which must be sheared is 88.8 sq. in. If the ultimate shear strength of the concrete is assumed to be 0.30 ksi, the shear strength of the connection is given as follows:

$V = (88.8 \text{ sq. in.})(0.30 \text{ ksi}),$

$V = 26.6 \text{ k.}$

The shear strength of this connection is thus calculated to be 27 k.

BENDING CAPACITY

The bending capacity, $M$, of this connection is zero because the connection has no tension capacity.

TORSION CAPACITY

To calculate the torsion capacity, $T$, of the connection it is assumed that the ultimate shearing strength of the concrete is 0.30 ksi and that the shearing stress distribution in the concrete protrusions is as shown in Figure 64. The torsion capacity of the connection is thus calculated as follows:

$T = (5.95 \text{ k})(10.6 \text{ in.}) + (.75 \text{ k})(3.8 \text{ in.}) + (5.20 \text{ k})(7.9 \text{ in.}),$

$T = 107 \text{ in.-k} \text{ or } 8.9 \text{ ft-k.}$

The torsion capacity of the connection is thus calculated to be 9 ft-k.
Figure 62. Tongue and Groove (Oregon).
Figure 63. Shearing Stress Distribution in Barrier Tongue When Connection is in Shear.
Figure 64. Shearing Stress Distribution in Tongue When Connection is in Torsion.

F_1 = 5.95 k, F_2 = 0.75 k, F_3 = 5.20 k
TONGUE AND GROOVE (Virginia)

The Virginia tongue and groove connection is shown in Figure 65. A single vertical protrusion is cast into one end of the barrier section and a groove is cast into the other end. The connection is accomplished by inserting the protrusion on one end of a barrier section into the groove on the other end of another barrier.

**TENSION CAPACITY**

The tension capacity, $F_T$, of this connection is zero because there is no positive attachment.

**SHEAR CAPACITY**

The shear capacity, $V$, of this connection is controlled by the force required to shear the concrete protrusion from the end of the barrier section as shown in Figure 66. The area of the protrusion that must be sheared is 107.6 sq. in. If the ultimate shear strength of the concrete is assumed to be 0.30 ksi, the shear strength of the connection is calculated as follows:

$$V = (107.6 \text{ sq in.})(0.30 \text{ ksi}),$$

$$V = 32.3 \text{ k}.$$

The shear capacity of the connection is thus calculated to be 32 k.

**BENDING CAPACITY**

The bending capacity, $M$, of this section is zero because the tension capacity of the connection is zero.

**TORSION CAPACITY**

To calculate the torsion capacity, $T$, of this connection it is assumed that the ultimate shear strength of the concrete is 0.30 ksi and that the shearing stress distribution shown in Figure 67 acts in the concrete protrusion. The torsion capacity of the section is then given as follows:

$$T = (6.4 \text{ k})(13.6 \text{ in.}),$$

$$T = 87.0 \text{ in.-k} \text{ or } 7.3 \text{ ft-k}.$$

The torsion capacity of this connection is thus calculated to be 7 ft-k.
Figure 65. Tongue and Groove (Virginia).
Figure 66. Shearing Stress Distribution in Tongue When Connection is in Shear.
(a) Barrier Cross-Section

(b) Assumed Shearing Stress Distribution

\[ F_1 = 6.4 \text{ k}, \quad F_2 = 6.4 \text{ k} \]

Figure 67. Shearing Stress Distribution in Tongue When Connection is in Shear.
The Colorado top hook and rebar connection is shown in Figure 68. Steel loops are cast into both ends of the barrier section. The barrier connection is accomplished by installing the steel hook as shown in Figure 68.

**TENSION CAPACITY**

The tensile capacity, $F_T$, of this connection is controlled by the strength of the steel hook (Ref. Fig. 69) or the strength of the steel loops (Ref. Fig. 70).

**TENSILE STRENGTH OF HOOK**

If the yield strength of the hook in tension is assumed to be 60 ksi, the tensile strength of the connection at point A (Ref. Fig. 69) is given as follows:

$$T = \pi \left(\frac{7}{16}\text{ in.}\right)^2 (60\text{ ksi})$$

$T = 36.1$ k.

**FLEXURAL STRENGTH OF HOOK**

If the yield strength of the hook in tension is assumed to be 60 ksi, the plastic moment capacity of the hook at point B, as shown in Figure 69, is given as follows:

$$M_{pl} = \frac{4}{3} \left(\frac{7}{16}\text{ in.}\right)^3 (60\text{ ksi})$$

$M_{pl} = 6.7$ in.-k.

The tensile capacity of the hook is then given as follows:

$$F_T = \frac{6.70\text{ in.-k}}{(15/16\text{ in.})},$$

$F_T = 7.1$ k.

**SHEAR STRENGTH OF HOOK**

If the yield strength of the hook in shear is assumed to be 34.6 ksi, the tensile strength of the connection is given as follows:

$$F_T = 34.6\text{ ksi} \ (\pi) \left(\frac{7}{16}\text{ in.}\right)^2,$$

$F_T = 20.8$ k.

**TENSILE STRENGTH OF LOOP**

If the yield strength of the loop in tension is assumed to be 60 ksi, the tensile strength of the loop loaded as shown in Figure 70 is given as follows:
Figure 68. Top Hook and Rebar (Colorado).
\[ F_T = 2(\pi)(5/16 \text{ in.})^2 (60 \text{ ksi}), \]
\[ F_T = 36.8 \text{ k}. \]
The tensile capacity of the connection is thus calculated to be 7 k.

**SHEAR CAPACITY**

The shear capacity, \( V \), of this connection is controlled by the shear strength of the hook loaded as shown in Figure 71, or the frictional resistance between the barrier sections in contact as shown in Figure 72.

**SHEAR STRENGTH OF HOOK**

The shear strength of the hook was previously calculated to be 20.8 k.

**FRICTIONAL RESISTANCE BETWEEN BARRIERS**

The maximum normal force between the barriers was previously determined to be 7.2 k. If the coefficient of friction between the concrete barriers is assumed to be 0.7 (Ref. Fig. 73), the shear strength of the connection is thus calculated to be 5. k.

\[ V = 0.7 (7.2), \]
\[ V = 5.0 \text{ k}. \]
The shear capacity of the connection is thus calculated to be 5 k.

**BENDING CAPACITY**

The bending capacity, \( M \), of this connection is controlled by the couple which develops between the tensile force in the hook and the compressive force between the concrete barriers in contact as shown in Figure 23. If the moment arm, \( d \), shown in Figure 23 is assumed to be 8 in., the bending strength of the connection is given as follows:

\[ M = (7.2 \text{ k})(8 \text{ in.}), \]
\[ M = 57.6 \text{ in.-k or 4.8 ft-k}. \]
The bending capacity of this connection is thus calculated to be 5 ft-k.

**TORSION CAPACITY**

The torsion capacity is controlled by the torque required to twist the hook loaded as shown in Figure 74. If it is assumed that the yield strength of the hook in shear is 34.6 ksi, the torsion capacity of the connection is given as follows:

\[ T = (2/3)(34.6 \text{ ksi})(7/16 \text{ in.})^3, \]
\[ T = 1.9 \text{ in.-k or 1.16 ft-k}. \]
The torsion capacity of the connection is thus calculated to be effectively zero.
Figure 69. Forces on Top Hook When Connection is in Tension.

Figure 70. Forces on Loop When Connection is in Tension.

Figure 71. Forces on Top Hook When Connection is in Shear.
Figure 72. Barrier Faces in Contact When Connection is in Shear.

Figure 73. Friction Forces on Barrier Face When Connection is in Shear.
Figure 74. Forces on Top Hook When Connection is in Torsion.
The TTl channel splice connection is shown in Figure 75. The barrier sections are fabricated with two bolt holes through the thickness of the barrier. The barrier connection is accomplished by connecting the barrier ends together using channel splice plates which are bolted to the barrier ends with bolts which go through the full width of the barrier section as shown.

**TENSILE CAPACITY**

The tensile capacity, $F_T$, of this connection is controlled by either the strength of the channel splice plates, or the strength of the bolts loaded as shown in Figure 76.

**TENSILE STRENGTH OF SPLICE**

If it is assumed that the yield strength of the splice in tension is 36 ksi, the tensile capacity of the connection is given as follows (Ref. Fig. 76):

$$F_T = 2[2.64 \text{ sq in.} - (7/4 \text{ in.})(.325 \text{ in.})](36 \text{ ksi}),$$

$$F_T = 149.1 \text{ k.}$$

**SHEAR STRENGTH OF BOLTS**

If it is assumed that the yield strength of the bolts in shear is 34.6 ksi, the tensile strength of the connection is given as follows:

$$F_T = 4(.70)(\pi)(9/16 \text{ in.})^2(34.6 \text{ ksi}),$$

$$F_T = 96.3 \text{ k.}$$

The tensile strength of the connection is thus calculated to be 96 k.

**SHEAR CAPACITY**

The shear capacity, $V$, of the connection is controlled by either the shear strength of the channel splice plate as shown in Figure 77, or the frictional resistance between the barrier ends in contact as shown in Figure 78.

**SHEAR STRENGTH OF SPLICE**

If the yield strength of the channel splice plate in shear is assumed to be 20.8 ksi, (Ref. Fig. 77) the shear strength of the connection is given as follows:

$$V = 2(2.64 \text{ sq. in.})(20.8 \text{ ksi}),$$

$$V = 109.8 \text{ k.}$$
Figure 75. Channel Splice.
Figure 76. Forces on Bolts and Channels When Connection is in Tension.

Figure 77. Forces on Channel When Connection is in Shear.
FRICTIONAL RESISTANCE BETWEEN BARRIERS

The maximum normal force between the barriers was calculated earlier to be 96.3 k. If the coefficient of friction between the barriers is assumed to be 0.7, the shear strength of the connection is given as follows (Ref. Fig. 79):

\[ V = 0.7(96.3 \text{ k}) \]
\[ V = 67.4 \text{ k} \]

The shear capacity of the connection is thus calculated to be 67 k.

BENDING CAPACITY

The bending capacity of this connection is controlled by the couple which develops between the splice plate in tension and the compressive force between the barriers in contact as shown in Figure 80. The maximum force in each channel was calculated to be 96.3/2 k. If the moment arm, d, shown in Figure 80 is assumed to be 20 in., the bending capacity of the connection is given as follows:

\[ M = (96.3/2 \text{ k})(20 \text{ in.}) \]
\[ M = 963.0 \text{ in.-k or 80.3 ft-k} \]

The bending capacity of the connection is thus calculated to be 80 ft-k.

TORSION CAPACITY

The torsion capacity of this connection is controlled by the couple which develops in the channel splice plates as shown in Figure 81. The force in the splice plates is limited by either the shear or bending capacity of the splice plates loaded as shown in Figure 82.

SHEAR STRENGTH OF SPLICE PLATES

If the yield strength of the splice plates in shear is assumed to be 20.4 ksi, the torsion capacity of the connection is given as follows:

\[ T = (2.64 \text{ sq. in.})(20.4 \text{ ksi})(22 \text{ in.}) \]
\[ T = 1184.8 \text{ in.-k or 98.7 ft-k} \]

BENDING STRENGTH OF SPLICE PLATES

If the yield strength of the splice plates in tension is assumed to be 36 ksi, the plastic moment capacity of the section is given as follows:

\[ M_{pl} = 2[(2.18 \text{ in.})(.325 \text{ in.})(36 \text{ ksi})(2.18 \text{ in.}/2) + (1.56 \text{ in.})(.32 \text{ in.})(2.34 \text{ in.})(36 \text{ ksi})] \]
\[ M_{pl} = 139.7 \text{ in.-k} \]
Figure 78. Connection in Shear.

Figure 79. Frictional Forces on Barrier Face When Connection is in Shear.
Figure 80. Forces on Barrier Face When Connection is in Bending.

Figure 81. Forces on Channels When Connection is in Torsion.
Figure 82. Forces on Channel When Connection is in Torsion.
The torsion capacity of the section is then given as follows:
\[ T = \left( \frac{2}{25 \text{ in.}} \right) (139.7 \text{ in.-k})(22 \text{ in.}), \]
\[ T = 245.9 \text{ in.-k} \text{ or } 20.5 \text{ ft-k}. \]

The torsion capacity of this connection is thus calculated to be 21 ft-k.
The TTI T-Lock connection is shown in Figure 83. Vertical holes are cast into the bottom ends of the barrier section as shown. The holes are aligned so that they mate with the vertical members of the steel T-Lock. The connection is accomplished by placing the steel T-Lock in position and lifting the barrier sections onto the T-Lock as shown in Figure 83.

**TENSILE CAPACITY**

The tensile capacity, $F_T$, of this connection is controlled by the strength of the steel T-Lock loaded as shown in Figure 84. This strength is limited by either the tensile strength of the horizontal structural tube or the shearing strength of the vertical end pipes.

**TENSILE STRENGTH OF STRUCTURAL TUBE**

If it is assumed that the yield strength of the structural tube in tension is 46 ksi, the tensile capacity of the connection is given as follows:

$$F_T = (8.36 \text{ sq. in.})(46 \text{ ksi}),$$

$$F_T = 384.6 \text{ k}.$$  

**SHEAR STRENGTH OF VERTICAL PIPE**

If it is assumed that the yield strength of the pipe tube in shear is 20.8 ksi, the tensile capacity of the connection is given as follows:

$$F_T = (2.23 \text{ sq. in.})(20.8 \text{ ksi}),$$

$$F_T = 46.4 \text{ k}.$$  

The tensile capacity of the connection is thus calculated to be 46 k.

**SHEAR CAPACITY**

The shear capacity, $V$, of this connection is controlled by the strength of the steel T-Lock loaded as shown in Figure 85. If the yield strength of the structural tube in shear is assumed to be 26.6 ksi, the shear strength of the connection is given as follows:

$$V = [8.36 \text{ sq. in.} + 13.75 \text{ sq. in.}](26.6 \text{ ksi}),$$

$$V = 588.1 \text{ k}.$$  

The shear strength of this connection is thus calculated to be 588 k.
Figure 83. T-Lock (Base).
Figure 84. Forces on T-Lock When Connection is in Tension.

Figure 85. Shearing Forces on T-Lock When Connection is in Shear.
BENDING CAPACITY

The bending capacity, $M$, of this connection is the result of the combined actions of the couple which develops between the tensile force in the T-Lock and the compressive force between the barrier ends in contact (Ref. Fig. 23), and the bending strength of the structural tube. The combined bending capacities are closely approximated by simply summing the two effects. If it is assumed that the yield strength of the structural tube is 46 ksi, the bending capacity of the connection is given as follows:

$M = 2[(3 \text{ in.})(1 \text{ in.})(1.5 \text{ in.})+(3 \text{ in.})(.5 \text{ in.})(2.75 \text{ in.})](46 \text{ ksi})+(46.4 \text{ ksi})(8 \text{ in.})$.

$M = 1164.7 \text{ in.-k} \text{ or 97.1 ft-k}.$

The moment capacity of the connection is thus calculated to be 97 ft-k.

TORSION CAPACITY

The torsion capacity of the connection is controlled by the strength of the steel T-Lock with the assumed shear stress distribution shown in Figure 86. If the yield strength of the structural tube in shear is assumed to be 26.6 ksi, the torsion capacity of the connection is given as follows:

$T = (294 \text{ k})(11.1 \text{ in.})+(71.7 \text{ k})(2.7 \text{ in.})+(222.3 \text{ k})(4.7 \text{ in.})$.

$T = 4501.8 \text{ in.-k} \text{ or 375.2 ft-k}.$

The torsion capacity of the connection is thus calculated to be 375 ft-k.
Figure 86. Shearing Forces on T-Lock When Connection is in Tension.
T-LOCK (TOP)

The Harris county T-Lock connection is shown in Figure 87. Vertical holes are cast into the top ends of the barrier section as shown. The holes are aligned so that they mate with the vertical members of the steel T-Lock. The connection is accomplished by positioning the barrier sections end to end and then lowering the T-Lock into place from the top as shown in Figure 87.

TENSILE CAPACITY

The tensile capacity, $F_T$, of this connection is controlled by the strength of the steel T-Lock loaded as shown in Figure 88. This strength is limited by either the tensile strength of the horizontal steel channel, or the shearing strength of the vertical steel pins.

TENSILE STRENGTH OF CHANNEL

If it is assumed that the yield strength of the steel channel in tension is 36 ksi, the tensile capacity of the connection is give as follows:

$F_T = (1.59 \text{ sq. in.})(36 \text{ ksi}),$

$F_T = 57.2 \text{ k.}$

SHEARING STRENGTH OF PINS

If it is assumed that the yield strength of the steel pins in shear is 20.8 ksi, the tensile capacity of the connection is given as follows:

$F_T = \pi(0.5 \text{ in.})^2(20.8 \text{ ksi}),$

$F_T = 16.3 \text{ k.}$

The tensile strength of the connection is thus calculated to be 16. k.

SHEAR CAPACITY

The shear capacity of the connection is controlled by the strength of the steel T-Lock with the assumed shearing stress distribution shown in Figure 89. If it is assumed that the yield strength of the steel channel in shear is 20.8 ksi and that the yield strength of the structural tube in shear is 26.6 ksi, the shear strength of the connection is given as follows:

$V = (1.59 \text{ sq. in.})(20.8 \text{ ksi}) + (12 \text{ in.})(1/2 \text{ in.})(26.6 \text{ ksi}),$

$V = 192.7 \text{ k.}$

The shear strength of this connection is thus calculated to be 193 k.
Figure 87. T-Lock (Top).
Figure 88. Forces on T-Lock When Connection is in Tension.

(a) Cross-Section of T-Lock in Shear
(b) Assumed Shearing Stress Distribution

\[ F_1 = 33.1 \text{ k}, F_2 = 159.6 \text{ k} \]

Figure 89. Forces on T-Lock When Connection is in Shear.
BENDING CAPACITY

The bending capacity, M, of this connection is controlled by the couple which develops between the tensile force in the T-Lock and the compressive force between the barrier ends in contact as shown in Figure 23. If the moment arm, d, in Figure 23 is assumed to be 8 in., the moment capacity of the connection is given as follows:

\[ M = (16.3 \text{ k})(8 \text{ in.}), \]
\[ M = 130.4 \text{ in.-k or } 10.9 \text{ ft-k}. \]

The bending capacity of this connection is thus calculated to be 11 ft-k.

TORSION CAPACITY

The torsion capacity, T, of this connection is controlled by the strength of the T-Lock with the assumed shear stress distribution shown in Figure 90. If the yield strengths of the channel and the structural tube are assumed to be 20.8 ksi and 26.6 ksi respectively, the torsional capacity of this connection is given as follows:

\[ T = 96.4 \text{ k}(3.6 \text{ in.}) + 63.3 \text{ k}(2.4 \text{ in.}) + 33.1 \text{ k}(5.2 \text{ in.}), \]
\[ T = 671.1 \text{ in.-k or } 55.9 \text{ ft-k}. \]

The torsion capacity of this connection is thus calculated to be 56 ft-k.
(a) Cross-Section of T-Lock in Torsion

(b) Assumed Shearing Stress Distribution

\[ F_1 = 33.1 \text{ k}, \quad F_2 = 63.3 \text{ k}, \quad F_3 = 96.4 \text{ k} \]

Figure 90. Forces on T-Lock When Connection is in Torsion.
The Texas grid-slot connection is shown in Figure 91. An orthogonal connection grid is fabricated by welding three horizontal steel bars welded to two vertical steel bars as shown in Figure 91. Identical vertical slots are cast into each end of the barrier segments. The connection is accomplished by aligning the ends of two barrier sections and inserting the steel grid described above into the slot. In permanent installations the grid is then grouted in place; however, in temporary installations grout is not used.

**TENSILE CAPACITY**

The tensile capacity, $F_T$, of this connection is zero because there is no positive connection between the barrier section ends.

**SHEAR CAPACITY**

The shear capacity, $V$, of this connection is controlled by either the shear strength (ref. Fig. 92) or bending strength (ref. Fig. 93) of the horizontal grid bars.

**SHEAR STRENGTH OF GRID BARS**

If it is assumed that the shear strength of the grid bars in shear is 34.6 ksi, the shear strength of the connection is given as follows:

$$V = 3 \pi (0.5 \text{ in.})^2 (34.6 \text{ ksi}),$$

$$V = 81.5 \text{ k.}$$

**BENDING STRENGTH OF GRID BARS**

If it is assumed that the yield strength of the grid bars in tension is 60 ksi, the plastic moment capacity of the bars is calculated as follows:

$$M_{pl} = \frac{4}{3} (0.5 \text{ in.})^3 (60 \text{ ksi}),$$

$$M_{pl} = 10.0 \text{ in.-k.}$$

If it is then assumed that the moment arm, $d$, shown in Figure 93 is assumed to be 1 in., the shear strength of the connection is given as follows:

$$V = 3(2)(10 \text{ in.-k/1 in.}),$$

$$V = 60 \text{ k.}$$

The shear capacity of the connection is thus calculated to be 60 k.
Figure 91. Grid-Slot (Texas).
Figure 92. Shear Forces on Grid Bars When Connection is in Shear.

Figure 93. Grid Bars in Bending When Connection is in Shear.
BENDING CAPACITY

The bending capacity, $M$, of this connection is zero because grout is not used in temporary connections.

TORSION CAPACITY

It is assumed that the torsional capacity, $T$, of this connection is the results of the couple which develops between the two outer grid bars as shown in Figure 94. It was seen earlier that the maximum shear force in the bars is limited by the bending strength of the bars. If it is assumed that the plastic moment capacity of the grid bars is 10 in.-k as calculated earlier, the torsion capacity of the connection is given as follows:

$$T = 2(10 \text{ in.-k/1 in.}) (18 \text{ in.}),$$

$$T = 360 \text{ in.-k} \text{ or } 30 \text{ ft-k}.$$  

The torsion capacity of the connection is thus calculated to be 30 ft-k.
Figure 94. Forces on Outer Grid Bars When Connection is in Torsion.
BARRIERS IN CONSTRUCTION ZONES

APPENDIX E

Cost of Portable Concrete Barriers

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by
Roger J. Koppa
Research Psychologist

Texas A&M Research Foundation
Texas Transportation Institute
The Texas A&M University System
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THE COST OF PORTABLE CONCRETE BARRIERS

INTRODUCTION

In order to develop a solid basis for comparative ratings of portable concrete barrier concepts, a number of cost estimates were performed on various aspects of fabricating, installing, relocating, maintaining, and removing these barriers at construction sites. Some of this work was based on field observations carried out in the early summer of 1983, and some was based on estimates of the tasks, manpower and equipment times and costs that it might take to perform these operations. As will be described below, man-minute and equipment-time estimates for analytic cases were based on standard construction industry information such as that obtainable from the Dodge Manual (8). Other pricing guides were used as a backup, and industrial engineering standard references were used to estimate time for jobs such as joint fabrication.

Ten different portable concrete barrier (PCB) concepts were used in this analysis. They run the gamut so far as joint design is concerned, from the very simplest tongue-and-groove or mortise design to the very complex Welsbach interlocking joint. All but one of these joints (Bottom T-Lock, Concept C-8) are in use somewhere in the United States. Except for details of reinforcing steel and hardware cast into the body of the barrier itself, these ten concepts differ only in the joint design. Each design is also considered for three different lengths: 10, 20, and 30 ft. Other lengths, of course, are both feasible and occasionally found in use, but the results of the analyses presented in this chapter can readily be interpolated for any length less than 30 ft. For lengths greater than 30 ft, physical limitations of cranes and flatbed truck trailers assumed or observed in this study would greatly and nonlinearly change these cost estimates.

The ten concepts are as follows:

C1: Tongue and Groove
C2: Steel Dowel Joint
C3: Grid Slot—a Gridiron inserted down a slot in the ends of abutting PCB's
C4: Top T-Lock—a T-shaped connector is pinned on each side of a joint
C5: Lapped joint--each end of a PCB at a joint is scarfed to overlap, with a single bolt holding the joint together.

C6: Pin and Re-Bar--a long bolt drops through rings embedded in the ends of each PCB to form a hinge-like joint.

C7: Vertical I-Beam--the joint consists of an I-beam which is dropped through a split pipe embedded in each PCB end.

C8: Bottom T-Lock--somewhat like C4, but pins become short pipe ends, and the PCB's are placed over the joint assembly.

C9: Channel Splice--Channel sections are bolted across the two PCB ends to form the joint.

C10: Welsbach--steel T-hooks engage matching slots in the mating end of a PCB to form an interlocking joint.

These ten joint concepts are pictured in Figures 95 through 104. Detailed technical descriptions and further views of these joints and the reinforcing structures required in their respective barrier structure are given in Appendix D.

Field research was performed in the late spring and early summer of 1983 to witness first hand actual operations by several different contractors and to conduct time and motion studies of representative PCB handling procedures. With the very kind assistance of the Texas State Department of Highways and Public Transportation, resident maintenance engineers in all the major urban districts of the Department were contacted and asked to alert TTI researchers when movement, installation, or removal of PCB's was scheduled in their district. Three field trips resulted from this. Each trip followed the same protocol.

Researchers traveled to the site and checked in with the SDHPT supervisor, and the contractor supervisor. After observing several cycles of manipulation of the PCB's, individual procedure times were taken by stopwatch. Still photographs of the joint design and representative stages in the moving, loading, and placement of PCB's, etc. were made. Then several complete cycles were videotaped. Supervisory personnel were debriefed to clear up any details. The procedure followed the format given in Figure 105, which is a reproduction of the field visit data sheet. The three sites visited were:
Figure 95. Joint Concept C1--Tongue and Groove.
Figure 96. Joint Concept C2--Dowel.
Figure 97. Joint Concept C3--Grid-Slot.
Figure 98. Joint Concept C4--T-Lock.
Figure 99. Joint Concept C5--Lapped Joint and Bolt.
Figure 100. Joint Concept C6-Pin and Rebar.
Figure 101. Joint Concept C7--I-Lock.
Figure 102. Joint Concept C8--T-Lock.
Figure 103. Joint Concept C9--Channel Splice.
Figure 104. Joint Concept C10--Welsbach Interlock.
Project RF3825: "Development of Safer Barriers for Construction Sites" (DOT-FH-11-9458).

TASK 1: Barrier Rating System

1. Date __________ District __________ TTI Observer __________
   Time __________ Contact ________________________________
   To __________ Site Supervisor __________________________
   Location: Highway ______ Direction ______ Specifics ________
   Film Roll# __________ Exposures ________ to __________
   Video Cartridge# ______________________________________

2. Barrier Type: ( ) PCB: ( ) 12 ( ) 15 ( ) 24 ( ) 30 ( ) Other __________
   Joint: ( ) None
   ( ) Tongue and groove
   ( ) Positive Joint
   ( ) Other design
   ( ) Other type (specify) ________________________________

Figure 105. Field Visit Data Sheet.
3. **Operation:**

\( \square \) Barrier Placement  
\( \square \) Barrier Relocation  
\( \square \) Barrier Removal  
\( \square \) Other (Specify) ________________

<table>
<thead>
<tr>
<th>Operation</th>
<th>Sections</th>
<th>Personnel Directly Involved</th>
<th>Personnel Traffic Control</th>
<th>Personnel other duties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. **Sections:** __________ Sections or __________ ft. Total during Observation Period

5. **Crew Size:** ( ) Supervisor(s) __________________

<table>
<thead>
<tr>
<th>Personnel Directly Involved</th>
<th>Personnel Traffic Control</th>
<th>Personnel other duties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. **Equipment**

( ) A. Trucks: _______ Trucks (Specify Types) ________________

( ) B. Crane: Describe: ______________________________

( ) C. Forklift: Describe: ______________________________

( ) D. Other Heavy Equipment (Specify) __________________

( ) E. Small Tools Used (Specify) ____________________

---

**Figure 105. Field Visit Data Sheet. (Continued)**
### Time Estimates

<table>
<thead>
<tr>
<th>Suboperation</th>
<th>Beginning Point</th>
<th>End Point</th>
<th>Elapsed time:</th>
<th>Manpower engaged</th>
<th>___ min.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 105. Field Visit Data Sheet. (Continued)
8. Total Elapsed Time for _________________________ Sections or _________________________ ft. Handled.

REMARKS: ______________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________
_______________________________________________________________

Figure 105. Field Visit Data Sheet. (Continued.)
(1) State Highway 288, just north of city limits of Angleton, Texas. This was a relocation job, ancillary to widening the pavement. The barriers were of the C9 type, Channel Splice.

(2) I-35 west of Dallas downtown area, relocation job to protect the median while the median barrier was being improved from a Steel W-beam to a concrete median barrier. The type joint was C5--Lapped Joint.

(3) I-10, west of Houston, PCB placement job, as part of a creation of a median dedicated lane for mass transitway. These barriers will ultimately become permanent CMB's. The joint design was C3--Grid Slot.

COSTS OF FABRICATION OF PORTABLE CONCRETE BARRIERS

Estimates for Casting Barriers

Cost estimates for casting the main structure of Portable Concrete Barriers (PCB) were derived from several sources. The Dodge Manual (8) indicates a cost per linear foot of nearly 84 dollars for the construction of precast beams for construction which are approximately the size (though not shape nor for the same purpose) of PCB. This compares with a cost to TTI for special experimental PCB's of $80 per foot. Reports from other sources in State Highway Departments suggest that in large quantities which would characterize operational purchases of PCB, the price for these barriers would be of the order of 16 to 30 dollars per ft. The 16 dollar price is for materials, casting, and labor exclusive of any special provisions for joints. For purposes of comparing different concepts, since they differ principally in the design of the joint, a figure of $16.00 per linear foot will be used throughout this chapter. This value is a reasonable approximation of cost to produce without overhead or profit to the contractor, i.e., direct costs to fabricate.

Estimates of Joint Fabrication Costs

It was necessary to make a number of assumptions in analyzing the work and materials involved in fabricating joints. The 20-city labor cost average from the Dodge Manual was used as a basis for all fabrication labor, with
categories of general worker or laborer, welder, skilled metal worker/machinist. These labor costs do not include overhead or profit by the contractor, but do include fringe benefits, and a 22 percent surcharge for insurance and taxes. They are as follows:

- General labor -------- $16.54 per hour
- Welder -------------- $20.00 per hour
- Skilled machinist --- $21.50 per hour

Material costs were obtained by inquiry to several local suppliers of building and construction metal. Fabrication times were estimated by using the following rationale:

It was assumed that no special tooling or mandrels except for stamped metal parts would be used, but rather fabrication would involve only general shop machinery such as drill presses, lathes, brakes, bending machines, electric arc welders, etc. It was assumed that suitable modifications could be made in any PCB casting assembly to accommodate the joint system without extra cost to the major casting operation. Another assumption was that fasteners, i.e. bolts and nuts, would be purchased at commercial rates and not specially fabricated. Costs for the purchase of these items was estimated from the Dodge Manual, with cross check of prices in Engelsman (9). Cutting, welding and forming man-minute rates were estimated by reference to standard sources, such as Niebel (10) and Kent (11). These estimates should thus be considered to be very conservative, i.e. high, since a large contract to fabricate PCB would lead most fabricators to invest in some kind of special tooling and mass-production techniques to facilitate joint fabrication. Although the cost per joint might be less if mass-production techniques were used, the relative cost of fabrication of one joint vs. another should hold.

Analysis, with a good measure of engineering judgement, of the ten different PCB joints yielded Table 13. Each joint is considered as a unit. Column 1 identifies the concept, column 2 briefly lists the hardware that must be fabricated or procured to make the joint. The manufacturing operations needed to ready the joint parts for incorporation in the casting of the PCB's are listed in Column 3. These costs range from a minimum of about three dollars for C1-Tongue and Groove to a high of 87 dollars for the complex Welsbach design (C10).
Table 13. Joint Fabrication Cost Analysis

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>HARDWARE MFG</th>
<th>MFG OPRNS</th>
<th>NAT'L LABOR</th>
<th>TOTAL</th>
<th>NEAREST</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-Tongue &amp; Groove</td>
<td>Nose Cap over Tongue</td>
<td>Cut Stamp</td>
<td>$2.40</td>
<td>$0.69</td>
<td>$3.09</td>
</tr>
<tr>
<td>C2-Dowel</td>
<td>Steel Rods</td>
<td>Cut</td>
<td>$3.20</td>
<td>$0.33</td>
<td>$3.53</td>
</tr>
<tr>
<td>C3-Grid Slot</td>
<td>Grid of Steel Bar</td>
<td>Cut Weld</td>
<td>$5.33</td>
<td>$1.69</td>
<td>$7.02</td>
</tr>
<tr>
<td>C4-Top T-Lock</td>
<td>Channel Tubes Plates Pins</td>
<td>Cut Drill Weld</td>
<td>$9.00</td>
<td>$3.52</td>
<td>$12.52</td>
</tr>
<tr>
<td>C5-Lapped Joint</td>
<td>Bolt Re-Plates</td>
<td>Cut Notch Drill</td>
<td>$8.55</td>
<td>$1.72</td>
<td>$10.27</td>
</tr>
<tr>
<td>C6-Pin &amp; Rebar</td>
<td>Rebars Bolt</td>
<td>Cut &amp; Form Bars</td>
<td>$13.62</td>
<td>$7.08</td>
<td>$20.70</td>
</tr>
<tr>
<td>C7-Vertical I-Beam</td>
<td>I-Beam Tubes Re-Plates</td>
<td>Cut Slot Weld</td>
<td>$24.27</td>
<td>$14.82</td>
<td>$39.09</td>
</tr>
<tr>
<td>C8-Bottom T-Lock</td>
<td>Tube Base Pipe Tubes</td>
<td>Cut Split Weld</td>
<td>$34.00</td>
<td>$4.15</td>
<td>$38.15</td>
</tr>
<tr>
<td>C9-Channel Splice</td>
<td>Channel 4 Bolts Re-Plates</td>
<td>Cut Drill Clear</td>
<td>$50.00</td>
<td>$5.35</td>
<td>$55.35</td>
</tr>
<tr>
<td>C10-Welsbach</td>
<td>T-Rails L-Anchors Socket Assy. Anchors</td>
<td>Cut Form Bend Weld</td>
<td>$45.96</td>
<td>$41.16</td>
<td>$87.12</td>
</tr>
</tbody>
</table>
These joint fabrication costs operate on the base cost of 16 dollars per linear foot for casting PCB as shown in Table 14 for three different lengths of PCB, 10 ft, 20 ft, and 30 ft. Obviously, cost per foot decreases as the length of PCB increases. These costs run from a minimum of $16.10 for a 30 ft tongue-and-groove PCB to $24.70 for a 10 ft Welsbach jointed section.

COST ESTIMATES FOR BARRIER ASSEMBLY, DISASSEMBLY, AND RELOCATION

**Bases for Cost Estimates**

The primary basis for estimating the costs of moving barriers, i.e.

1. Picking up barrier sections from a depot, transporting them to a construction site, and placing them
2. Relocating barrier sections from one location to another within a construction site as the work progresses
3. Picking up barrier sections and returning them to a depot,

was observation of typical operations of this type at three construction sites, was the C9--Channel Splice concept at Angleton on 288, the C5--Lapped Joint on Stemmons Freeway, Interstate 35 in Dallas, and the C3--Grid Slot on I-10 west of Houston. Tables 15 through 20 summarize the tasks, work crew and equipment observed during these site visits. Table 21 summarizes these observations in terms of man-minutes of labor required, plus adds some estimated times based on similarity to these operations.

Some contractors were much more labor-intensive than others in the operation of hoisting and placing these barriers. One such operational sequence is depicted in Figures 106 through 108. In Figure 106, two men place hoisting rods and lifting cables in place up on the flatbed trailer (note that four barriers are carried at one time). Two other workers wait below. Four men under a supervisor's direction are used to maneuver the barrier section into place (one of the workers, just before final placement, places a plywood spacer between the sections to assure proper clearance for the joint. In Figure 108, the workers are shown removing the hoisting rods after final placement of the section. A typical time for this operation was 2 minutes. Figure 109 shows the extreme simplicity of installing the Grid Slot.
# Table 14. Fabrication Costs

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>LENGTH (FT)</th>
<th>JOINT COST</th>
<th>TOTAL COST/FT.</th>
<th>TOTAL COST PER SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-Tongue and</td>
<td>10</td>
<td>3.00</td>
<td>16.30</td>
<td>163.00</td>
</tr>
<tr>
<td>Groove</td>
<td>20</td>
<td>3.00</td>
<td>16.15</td>
<td>323.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>3.00</td>
<td>16.10</td>
<td>483.00</td>
</tr>
<tr>
<td>C2-Dowell</td>
<td>10</td>
<td>4.00</td>
<td>16.40</td>
<td>164.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4.00</td>
<td>16.20</td>
<td>324.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>4.00</td>
<td>16.13</td>
<td>484.00</td>
</tr>
<tr>
<td>C3-Grid Slot</td>
<td>10</td>
<td>7.00</td>
<td>16.70</td>
<td>167.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>7.00</td>
<td>16.35</td>
<td>327.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>7.00</td>
<td>16.23</td>
<td>487.00</td>
</tr>
<tr>
<td>C4-Top T-Lock</td>
<td>10</td>
<td>13.00</td>
<td>17.30</td>
<td>173.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>13.00</td>
<td>16.65</td>
<td>333.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>13.00</td>
<td>16.43</td>
<td>493.00</td>
</tr>
<tr>
<td>C5-Lapped Joint</td>
<td>10</td>
<td>10.00</td>
<td>17.00</td>
<td>170.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10.00</td>
<td>16.50</td>
<td>330.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>10.00</td>
<td>16.33</td>
<td>490.00</td>
</tr>
<tr>
<td>C6-Pin and Rebar</td>
<td>10</td>
<td>21.00</td>
<td>18.10</td>
<td>181.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>21.00</td>
<td>17.05</td>
<td>341.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>21.00</td>
<td>16.70</td>
<td>501.00</td>
</tr>
<tr>
<td>C7-Vertical I-Beam</td>
<td>10</td>
<td>39.00</td>
<td>19.90</td>
<td>199.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>39.00</td>
<td>17.95</td>
<td>359.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>39.00</td>
<td>17.30</td>
<td>519.00</td>
</tr>
<tr>
<td>C8-Bottom T-Lock</td>
<td>10</td>
<td>38.00</td>
<td>19.80</td>
<td>198.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>38.00</td>
<td>17.90</td>
<td>358.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>38.00</td>
<td>17.27</td>
<td>518.00</td>
</tr>
<tr>
<td>C9-Channel Splice</td>
<td>10</td>
<td>55.00</td>
<td>21.50</td>
<td>215.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>55.00</td>
<td>18.75</td>
<td>375.00</td>
</tr>
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<td></td>
<td>30</td>
<td>55.00</td>
<td>17.83</td>
<td>535.00</td>
</tr>
<tr>
<td>C10-Welsbach</td>
<td>10</td>
<td>87.00</td>
<td>24.70</td>
<td>247.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>87.00</td>
<td>20.35</td>
<td>407.00</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>87.00</td>
<td>18.90</td>
<td>567.00</td>
</tr>
</tbody>
</table>
Figure 106. Method 1 (Labor Intensive)--Placing Hoisting Rods.

Figure 107. Method 1--Maneuvering Section into Place.
Figure 108. Method 1--Removing Hoisting Rods after Placement.

Figure 109. Installation of Grid in Slot (Concept C3).
Table 15. Activity Analysis - Relocate 25 ft C9.

RF3025: DEVELOPMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>CREW</th>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Install eye bolts (2)</td>
<td>Remove from last PCB</td>
<td>Release</td>
<td></td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Attach lifting cables (2)</td>
<td>Grasp</td>
<td>Release 2nd</td>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Lift PCB</td>
<td>Tension Cables</td>
<td>PCB clear</td>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Move PCB to one side</td>
<td>PCB moves</td>
<td>PCB on ground</td>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Detach lifting cables (2)</td>
<td>Slack cables</td>
<td>Remove cable 2</td>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Remove eye bolts (2)</td>
<td>Grasp 1</td>
<td>Remove 2</td>
<td></td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Move Crane</td>
<td>Props retract</td>
<td>Props extend</td>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Crane</td>
<td>Drive</td>
</tr>
</tbody>
</table>

SUMMARY

<table>
<thead>
<tr>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 16. Activity Analysis - Disassemble 15 ft C9.

RF3825: DEVELOPMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Take off 8 Nuts</td>
<td>Wrench on 1</td>
<td>Wrench off 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pull Bolts</td>
<td>Pull 1</td>
<td>8 out</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Take off channels 4</td>
<td>Lay 1st down (drop 2 over from other side)</td>
<td>Lay 4 down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY

Note: about 25% of bolts are cross-threaded and stubborn about 1 in 40 must be cut with oxyacetylene torch.
Table 17. Activity Analysis - Load 30 ft C5.

RF3825: DEVELPOMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

ACTIVITY ANALYSIS

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Swing 'C' assembly into place</td>
<td>Lower assembly 'C' next to slots</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Secure 'C's into slots</td>
<td>C contacts slots 'C's in place</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Pick up PCB</td>
<td>Tension on Assembly PCB clear</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Swing PCB onto flatbed</td>
<td>PCB moves PCB on bed</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Trip 'C's from slots</td>
<td>Slack on Assembly 'C's clear</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Move crane</td>
<td>Props retract Props extend</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Move flatbed</td>
<td>Engage clutch Truck stops</td>
<td>1</td>
<td>1</td>
<td>1.5*</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

SUMMARY

Note: Supervisor was doubling as crane operator, but this would not be nominal procedure

EQUIPMENT
- Crane - 22 Ton
- C hooks on Bar
- Flatbed Trucks (3)

BARRIER PCB, C5 Lapped Joint & Bolt 30 ft.

ACTIVITY: Pick up PCB, place on Flatbed

\[ T = 0.97 \text{ min. } \sigma = 0.15 \text{ min. } N = 5 \]

C R E W

<table>
<thead>
<tr>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1.5*</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

*1 in position
1 at other end
1 in transit
<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>CREW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SUPER</td>
</tr>
<tr>
<td>1</td>
<td>Place bolt through lap joint holes</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Place nut on bolt</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Tighten nut on bolt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Loosen nut on bolt</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Remove nut</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pull out bolt</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SUMMARY**

Table 18. Activity Analysis - Bolt/unbolt C5.

RF3825: DEVELOPMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

ACTIVITY ANALYSIS

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>BARRIER</th>
<th>ACTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>30&quot; Ratchet Wrench</td>
<td>PCB, C5 Lapped Joint &amp; Bolt</td>
<td>Bolt/Unbolt Joint</td>
</tr>
<tr>
<td>30&quot; Socket Wrench</td>
<td></td>
<td>0.3 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>CREW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SUPER</td>
</tr>
<tr>
<td>1</td>
<td>Place bolt through lap joint holes</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Place nut on bolt</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Tighten nut on bolt</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| OR |                    |                            |     | SUPER | CRANE | TRUCK | HNDLR | OTHER | OTHER |
|    |                    |                            |     | 1     | 1     |       |       |       |       |
| 1   | Loosen nut on bolt |                           |     |       |       | 1     | 1     |       |       |
| 2   | Remove nut        |                           |     |       |       | 1     |       |       |       |
| 3   | Pull out bolt     |                           |     |       |       | 1     |       |       |       |

| SUMMARY |                            |     | SUPER | CRANE | TRUCK | HNDLR | OTHER | OTHER |
|         |                            |     | 1     | 1     |       |       |       |       |
Table 19. Activity Analysis - Place 30 ft C5.

RF3025: DEVELOPMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

ACTIVITY ANALYSIS

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>CREW</th>
<th>SUPER</th>
<th>CRANE</th>
<th>TRUCK</th>
<th>HNDLR</th>
<th>OTHER</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Swing 'C' assembly into place</td>
<td>Lower assembly</td>
<td>'C' next to slots</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Secure 'C's into slots</td>
<td>Get on truck</td>
<td>'C's in place</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pick up PCB</td>
<td>Tension on assembly</td>
<td>PCB clear</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Swing PCB into position</td>
<td>PCB moves</td>
<td>PCB in line</td>
<td>1</td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Position PCB</td>
<td>Gauge PCB Separation</td>
<td>PCB on ground</td>
<td>1</td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Trip 'C's from slots</td>
<td>Slack on assembly</td>
<td>'C's clear</td>
<td>1</td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Move crane</td>
<td>Props retract</td>
<td>Props extend</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Move flatbed</td>
<td>Engage clutch</td>
<td>Truck stops</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY

<table>
<thead>
<tr>
<th>SUPER</th>
<th>CRANE</th>
<th>1.5*</th>
<th>2</th>
</tr>
</thead>
</table>

*1 in position
1 at other end
1 in transit
Table 20. Activity Analysis - Place 30 ft C3.

RF3825: DEVELOPMENT OF SAFER BARRIERS FOR CONSTRUCTION SITES

ACTIVITY ANALYSIS

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT</th>
<th>BEGINNING</th>
<th>END</th>
<th>CREW</th>
<th>CREW</th>
<th>CREW</th>
<th>CREW</th>
<th>CREW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Place rods in PCB</td>
<td>Climb on Bed</td>
<td>2nd rod in place</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Attach cables (4) to rods</td>
<td>Grasp 1st cable</td>
<td>Climb down off bed</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Lift PCB off Flatbed</td>
<td>Tension cables</td>
<td>PCB clear</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Move flatbed forward</td>
<td>Engage clutch</td>
<td>Stop</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Move PCB into position</td>
<td>PCB moves</td>
<td>PCB in line</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Final position, gauging</td>
<td>Gauge inserted</td>
<td>PCB on ground</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Detach cables (4)</td>
<td>Slack cables</td>
<td>Unhook 4th</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pull rods from PCB</td>
<td>Grasp</td>
<td>2nd rod out</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Move crane</td>
<td>Props retract</td>
<td>Props extend</td>
<td>1</td>
<td>1</td>
<td>2*</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Summary

Note: Joint consists of grid dropped into complex slot. Done by one of handlers in lulls.

---

ACTIVITY Place PCB at Construction Site

$T = 2.09$ min $SD = 0.50$ min $N = 8$

EQUIPMENT 30 Ton Gallon

4 Flatbed Trucks
(haul 4 each)

BARRIER PCB 30', C3 Drop in Grid
Table 21. Summary of Man-Minutes for Operations.

*Comparison of PCB Designs with Respect to Disassembly, Pickup, Placement, Reassembly

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>DISASSY</th>
<th>PICKUP</th>
<th>PLACEMENT</th>
<th>REASSY</th>
<th>TOTALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3 Drop in Grid</td>
<td>0.10</td>
<td>9.00</td>
<td>12.54</td>
<td>0.10</td>
<td>21.74</td>
</tr>
<tr>
<td>C5 Lapped Joint</td>
<td>0.60</td>
<td>3.88</td>
<td>5.40</td>
<td>0.60</td>
<td>10.48</td>
</tr>
<tr>
<td>C9 Channel Splice</td>
<td>6.00</td>
<td>8.75</td>
<td>12.30</td>
<td>6.00</td>
<td>33.05</td>
</tr>
</tbody>
</table>

*Actual
Other Costs Estimated

<table>
<thead>
<tr>
<th>RANK ORDERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>B&amp;R Drop in Grid</td>
</tr>
<tr>
<td>Texas Lapped Joint</td>
</tr>
<tr>
<td>TTI Channel Splice</td>
</tr>
<tr>
<td>TYPICAL</td>
</tr>
</tbody>
</table>

*Exclusive of transportation costs.
Figure 110 depicts C-shaped hooks on a spreader beam which one contractor uses to expedite handling of the PCB's. The crew consists of only two individuals for maneuvering (and sometimes securing or releasing the hooks) with the supervisor operating the crane. Figure 111 shows the final placement operation, with a stick used as a spacer. Figure 112 shows the section finally in place. This operation takes about one minute of time with less than half the manpower.

Figure 114 depicts the C-5--Lapped Joint used in this installation. Figure 115 shows the equipment and workers necessary to assemble or disassemble a C9--Channel Splice joint, including the APU for the impact wrench.

For costing typical operations, it was assumed that most contractors would use the more labor-intensive, less specialized equipment approach for lifting and moving the sections. It was assumed that contractors would use forklift trucks for 10 ft sections, but a "cherry picker" or similar self-propelled crane (approximately 20 to 30 ton capacity) for longer sections. Contractors informed researchers that at least three flatbed trucks were used for relocating barrier sections within a construction zone (less than 2 miles) but five were used for initial placement from a depot, or for return to a depot if the depot was more than two but less than ten miles distant. These numbers were used in this analysis. It was further assumed that the crane or forklift was rented equipment, but trucks were owned by the contractor and hence only operating costs and five year straight-line depreciation were assumed, plus, of course, direct costs for operator or driver labor. These costs worked out as follows (8):

- Truck, flatbed, 1/2 day = $64
- Crane, 22 ton capacity, 1/2 day = $165
- Forklift, 9 ton capacity, 1/2 day = $138

Not considering direct costs for transportation but only labor required for operations at site, the labor man-minute estimates shown in Table 22 were derived, and used as a basis for further analysis.

Transportation of barrier sections was costed at $64 per truck for a 4-hour period, and $17.33 per hour for the driver.
Figure 110. Method 2 (Mechanized) C-hooks Used to Hoist Section.

Figure 111. Method 2--Initial Maneuvering Operation.
Figure 112. Method 2--Final Placement (Note shim usage).

Figure 113. Method 2--End of Procedure, C-hooks Released.
Figure 114. Lapped Joint (C5) Installed.

Figure 115. Workers Installing C9 Channel Splice Joints.
# Table 22. Labor in Moving PCB

Unit: Man Minutes (M-M)

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>DISASSEMBLY</th>
<th>PICKUP*</th>
<th>PLACEMENT*</th>
<th>REASSY</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI-Tongue &amp; Groove</td>
<td>0</td>
<td>2.69</td>
<td>3.00</td>
<td>0</td>
<td>1 (perhaps)</td>
</tr>
<tr>
<td>C2-Dowel</td>
<td>0</td>
<td>2.69</td>
<td>3.00</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>C3-Grid Slot</td>
<td>0.03</td>
<td>2.69</td>
<td>3.77</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td>C4-Top T-Lock</td>
<td>0.11</td>
<td>2.69</td>
<td>3.77</td>
<td>0.11</td>
<td>2</td>
</tr>
<tr>
<td>C5-Lapped Joint</td>
<td>0.17</td>
<td>2.69</td>
<td>3.00</td>
<td>0.17</td>
<td>3, 4</td>
</tr>
<tr>
<td>C6-Pin &amp; Rebar</td>
<td>0.55</td>
<td>2.69</td>
<td>3.77</td>
<td>0.55</td>
<td>2</td>
</tr>
<tr>
<td>C7-Vertical I-Beam</td>
<td>0.03</td>
<td>2.69</td>
<td>3.77</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td>C8-Bottom T-Lock</td>
<td>0</td>
<td>2.69</td>
<td>3.77</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>C9-Channel Splice</td>
<td>2.00</td>
<td>2.69</td>
<td>3.77</td>
<td>2.00</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>CI0-Welsback</td>
<td>0</td>
<td>2.69</td>
<td>3.77</td>
<td>0</td>
<td>1 &amp; 2</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Constrains replacement of individual sections.
2. Requires precise alignment and spacing (20% penalty on placement)
3. Bolts become damaged; disassembly cost can be much higher
4. Crew size 2 for disassembly/assembly

*Mean cost is average of 4 laborers @ 16.54
1 crane opr. @ 21.50 = 18.20
1 supervisor @ 21.50

Placement 12.42 M-M (including penalty)
Pickup 8.88 M-M
Cost Estimates for Relocating Barriers

A nominal job consisting of moving 1,000 ft of barrier was used throughout this, and the following movement analyses. Since 10 ft sections can be picked up by one man on a forklift, at a wage of $21.50 per hour, and he can place 1,000 ft of barrier in four hours, the cost of initial pickup is $21.50 \times 4/100 = \text{86 cents per section.} Costs of labor for a 30 ft section are, of course, much higher, $2.69, but since there are only 33 sections to be moved, the total cost of pickup is comparable. These cost estimates plus others are shown in Table 23. Note that transportation cost is invariant, since a 60,000 lb capacity flatbed, a standard size in the industry, can handle four 30 ft sections, four 20 ft sections, or twelve 10 ft sections.

Section placement costs are taken from Table 22 for the 30 ft section operations already described. The 10 ft sections are assumed to require a two man crew: one on a forklift at $21.50 per hour, and a worker on the ground to assist in placement and use the spacer at $16.54 per hour. These costs multiplied by a four-hour time period total $152 for 100 sections placed, or $1.52 per section.

Joint disassembly times are costed out from observational or analytic data summarized in Table 22, and then multiplied by the number of joints that must be disassembled for a 1,000 ft barrier. This same logic applies to assembly costs. Then equipment rentals are totalled in, assuming that equipment cannot be rented for less than a half-day, and indeed a 1,000 ft job would require four hours. Finally, total estimated costs for this 1,000 ft relocation within a site are presented. As a check on this entire analysis, several contractors doing work for the Texas State Department of Highways and Public Transportation were queried for the direct cost they charge for this same operation. These estimates were in the range of one dollar per foot, an excellent agreement with the results of this analysis.

The mean cost per foot for relocating 10 ft sections is $1.19, with a range of $1.11 to $1.54, whereas the mean cost for 30 ft sections is 95 cents, ranging from $.92 to $1.07. The major cost differential in this 25 per cent difference is attributable to joint disassembly and assembly operations, even thought less manpower is required for 10 ft sections. Twenty foot sections would tend to reflect a cost intermediate or more like the 30 ft sections, since handling equipment is much the same for these sections as it is for 30 foot sections.
Table 23. Job: Release 1000 ft of PCB.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-Tongue</td>
<td>10'</td>
<td>98</td>
<td>0</td>
<td>0</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.52</td>
<td>152.00</td>
<td>0</td>
</tr>
<tr>
<td>C1-Tongue</td>
<td>30'</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.00</td>
<td>99.00</td>
<td>0</td>
</tr>
<tr>
<td>C2-Dowel</td>
<td>10'</td>
<td>98</td>
<td>0</td>
<td>0</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.52</td>
<td>152.00</td>
<td>0</td>
</tr>
<tr>
<td>C2-Dowel</td>
<td>30'</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.00</td>
<td>99.00</td>
<td>0</td>
</tr>
<tr>
<td>C3-Grid</td>
<td>10'</td>
<td>98</td>
<td>.03</td>
<td>2.94</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>.03</td>
</tr>
<tr>
<td>C4-Grid</td>
<td>30'</td>
<td>31</td>
<td>.03</td>
<td>.93</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>.93</td>
</tr>
<tr>
<td>C4-Top &quot;T&quot;</td>
<td>10'</td>
<td>98</td>
<td>.11</td>
<td>10.78</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>.11</td>
</tr>
<tr>
<td>C4-Top &quot;T&quot;</td>
<td>30'</td>
<td>31</td>
<td>.11</td>
<td>3.41</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>3.41</td>
</tr>
<tr>
<td>C5-Lapped</td>
<td>10'</td>
<td>98</td>
<td>.17</td>
<td>16.66</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.52</td>
<td>152.00</td>
<td>.17</td>
</tr>
<tr>
<td>C5-Lapped</td>
<td>30'</td>
<td>31</td>
<td>.17</td>
<td>5.27</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.00</td>
<td>99.00</td>
<td>5.27</td>
</tr>
<tr>
<td>C6-PIN</td>
<td>10'</td>
<td>98</td>
<td>.55</td>
<td>53.90</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>102.00</td>
<td>.55</td>
</tr>
<tr>
<td>C6-PIN</td>
<td>30'</td>
<td>31</td>
<td>.55</td>
<td>17.05</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>17.05</td>
</tr>
<tr>
<td>C7-1 Beam</td>
<td>10'</td>
<td>98</td>
<td>.03</td>
<td>2.94</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>.03</td>
</tr>
<tr>
<td>C7-1 Beam</td>
<td>30'</td>
<td>31</td>
<td>.03</td>
<td>.93</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>.93</td>
</tr>
<tr>
<td>C8-Bottom &quot;T&quot;</td>
<td>10'</td>
<td>98</td>
<td>0</td>
<td>0</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>0</td>
</tr>
<tr>
<td>C8-Bottom &quot;T&quot;</td>
<td>30'</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>0</td>
</tr>
<tr>
<td>C9-Channel</td>
<td>10'</td>
<td>98</td>
<td>2.00</td>
<td>196.00</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>2.00</td>
</tr>
<tr>
<td>C9-Channel</td>
<td>30'</td>
<td>31</td>
<td>2.00</td>
<td>62.00</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>62.00</td>
</tr>
<tr>
<td>C10-Welsbach</td>
<td>10'</td>
<td>98</td>
<td>0</td>
<td>0</td>
<td>.86</td>
<td>86.00</td>
<td>400.00</td>
<td>1.82</td>
<td>182.00</td>
<td>0</td>
</tr>
<tr>
<td>C10-Welsbach</td>
<td>30'</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>2.69</td>
<td>88.77</td>
<td>400.00</td>
<td>3.77</td>
<td>124.41</td>
<td>0</td>
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</tbody>
</table>

**SUMMARY:**
Mean Cost/ft, 10' Sections = $1.19 range 1.11 to 1.54
Mean Cost/ft, 30' Sections = $ .95 range .92 to 1.07
25% penalty by going with 10' vs 30' sections
Cost Estimates for Initial Installation of Barriers

Costs for bringing barriers from a depot to the construction site can be estimated by considering this operation to be a special case of relocation, with the subtraction of the disassembly operation and the addition of two extra trucks and their drivers to keep up a steady flow from the depot to the site. Thus, for 1,000 ft of barrier, for each of the ten concepts, Table 24 was generated, again at the limiting case lengths of 10 and 30 ft. These costs closely correlate with those for relocation.

Costs for removal of these barriers in those cases in which the barriers are not going to be permanently installed somewhere on the site, can also be estimated in a similar way from the relocation analysis. The total cost of relocation is debited by the cost for assembly of joints, and credited by two extra trucks to transport the sections back to the depot for storage. This analysis is shown in Table 25.

Supplementary Data from State DOT's

A complementary study in the Texas Transportation Institute has obtained some preliminary work and cost estimates for operations similar to those discussed above. Researchers sent a questionnaire to cognizant construction engineers in North Carolina, Tennessee, Virginia and Florida. These results are summarized in Table 26. They are not inconsistent with the cost estimates produced analytically in this project. The joint concepts involved were (North Carolina) C6--Pin and Re-Bar, also C9--Channel Splice; (other States) Tongue and Groove (C1).

MAINTENANCE COST ESTIMATES FOR BARRIER
Assumptions and Basis of Estimates

There are many ways in which a portable concrete barrier can be impacted by passing traffic and damaged, but for the purposes of this analysis it was assumed that the supervising agency would not repair a section in situ but would allow a damaged section to remain unless it was no longer able to perform its function or redirecting an impinging motor vehicle. Hence in this analysis "maintenance" means outright replacement of one or more sections. Conversations with construction engineers suggest that this is not an unrealistic assumption.

A maintenance activity therefore consists of:
Table 24. Installation of PCB at Construction Site

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>RELOCATE TOTAL</th>
<th>LESS DISASSY</th>
<th>PLUS 2 MORE TRUCKS</th>
<th>TOTAL INSTALL</th>
<th>COST/FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-10 ft</td>
<td>1113</td>
<td>0</td>
<td>267</td>
<td>1380</td>
<td>1.38</td>
</tr>
<tr>
<td>C1-30 ft</td>
<td>917</td>
<td>0</td>
<td>267</td>
<td>1184</td>
<td>1.18</td>
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<tr>
<td>C2-10 ft</td>
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<td>0</td>
<td>267</td>
<td>1380</td>
<td>1.38</td>
</tr>
<tr>
<td>C2-30 ft</td>
<td>917</td>
<td>0</td>
<td>267</td>
<td>1184</td>
<td>1.18</td>
</tr>
<tr>
<td>C3-10 ft</td>
<td>1149</td>
<td>2.94</td>
<td>267</td>
<td>1413</td>
<td>1.41</td>
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<tr>
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<td>945</td>
<td>.93</td>
<td>267</td>
<td>1209</td>
<td>1.21</td>
</tr>
<tr>
<td>C4-10 ft</td>
<td>1165</td>
<td>10.78</td>
<td>267</td>
<td>1421</td>
<td>1.42</td>
</tr>
<tr>
<td>C4-30 ft</td>
<td>950</td>
<td>3.41</td>
<td>267</td>
<td>1213</td>
<td>1.21</td>
</tr>
<tr>
<td>C5-10 ft</td>
<td>1146</td>
<td>16.66</td>
<td>267</td>
<td>1396</td>
<td>1.40</td>
</tr>
<tr>
<td>C5-30 ft</td>
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<td>267</td>
<td>1190</td>
<td>1.19</td>
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<tr>
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<td>53.90</td>
<td>267</td>
<td>1465</td>
<td>1.47</td>
</tr>
<tr>
<td>C6-30 ft</td>
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<td>17.05</td>
<td>267</td>
<td>1227</td>
<td>1.23</td>
</tr>
<tr>
<td>C7-10 ft</td>
<td>1149</td>
<td>2.94</td>
<td>267</td>
<td>1413</td>
<td>1.41</td>
</tr>
<tr>
<td>C7-30 ft</td>
<td>945</td>
<td>.93</td>
<td>267</td>
<td>1211</td>
<td>1.21</td>
</tr>
<tr>
<td>C8-10 ft</td>
<td>1143</td>
<td>0</td>
<td>267</td>
<td>1410</td>
<td>1.41</td>
</tr>
<tr>
<td>C8-30 ft</td>
<td>943</td>
<td>0</td>
<td>267</td>
<td>1210</td>
<td>1.21</td>
</tr>
<tr>
<td>C9-10 ft</td>
<td>1535</td>
<td>196.00</td>
<td>267</td>
<td>1606</td>
<td>1.61</td>
</tr>
<tr>
<td>C9-30 ft</td>
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<td>62.00</td>
<td>267</td>
<td>1272</td>
<td>1.27</td>
</tr>
<tr>
<td>C10-10 ft</td>
<td>1143</td>
<td>0</td>
<td>267</td>
<td>1410</td>
<td>1.41</td>
</tr>
<tr>
<td>C10-30 ft</td>
<td>943</td>
<td>0</td>
<td>267</td>
<td>1210</td>
<td>1.21</td>
</tr>
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</table>

1000 ft of barrier
<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>RELOCATE COST</th>
<th>ASSEMBLY COST</th>
<th>TOTAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-10 ft</td>
<td>1113.00</td>
<td>0.00</td>
<td>1380.00</td>
</tr>
<tr>
<td>C1-30 ft</td>
<td>917.00</td>
<td>0.00</td>
<td>1184.00</td>
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<tr>
<td>C2-10 ft</td>
<td>1113.00</td>
<td>0.00</td>
<td>1380.00</td>
</tr>
<tr>
<td>C2-30 ft</td>
<td>917.00</td>
<td>0.00</td>
<td>1184.00</td>
</tr>
<tr>
<td>C3-10 ft</td>
<td>1149.00</td>
<td>2.94</td>
<td>1413.06</td>
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<tr>
<td>C3-30 ft</td>
<td>945.00</td>
<td>0.93</td>
<td>1211.07</td>
</tr>
<tr>
<td>C4-10 ft</td>
<td>1165.00</td>
<td>10.78</td>
<td>1421.22</td>
</tr>
<tr>
<td>C4-30 ft</td>
<td>950.00</td>
<td>3.41</td>
<td>1213.59</td>
</tr>
<tr>
<td>C5-10 ft</td>
<td>1146.00</td>
<td>16.66</td>
<td>1396.34</td>
</tr>
<tr>
<td>C5-30 ft</td>
<td>928.00</td>
<td>5.27</td>
<td>1189.73</td>
</tr>
<tr>
<td>C6-10 ft</td>
<td>1252.00</td>
<td>53.90</td>
<td>1465.10</td>
</tr>
<tr>
<td>C6-30 ft</td>
<td>977.00</td>
<td>17.05</td>
<td>1226.95</td>
</tr>
<tr>
<td>C7-10 ft</td>
<td>1149.00</td>
<td>2.94</td>
<td>1413.06</td>
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<tr>
<td>C7-30 ft</td>
<td>945.00</td>
<td>0.93</td>
<td>1211.07</td>
</tr>
<tr>
<td>C8-10 ft</td>
<td>1143.00</td>
<td>0.00</td>
<td>1410.00</td>
</tr>
<tr>
<td>C8-30 ft</td>
<td>943.00</td>
<td>0.00</td>
<td>1210.00</td>
</tr>
<tr>
<td>C9-10 ft</td>
<td>1535.00</td>
<td>196.00</td>
<td>1606.00</td>
</tr>
<tr>
<td>C9-30 ft</td>
<td>1067.00</td>
<td>62.00</td>
<td>1272.00</td>
</tr>
<tr>
<td>C10-10 ft</td>
<td>1143.00</td>
<td>0.00</td>
<td>1410.00</td>
</tr>
<tr>
<td>C10-30 ft</td>
<td>943.00</td>
<td>0.00</td>
<td>1210.00</td>
</tr>
</tbody>
</table>
Table 26: Summary of Self Reports from State DOT's

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>N. Carolina Winston-Salem</th>
<th>N. Carolina Old Fort</th>
<th>Tennessee Site 1</th>
<th>Tennessee Site 2</th>
<th>Virginia</th>
<th>Florida</th>
<th>Mean Times or Mean Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relocation</td>
<td>6.00 m-m</td>
<td>0.30 m-m</td>
<td>5.40 m-m</td>
<td>-</td>
<td>6.00 m-m</td>
<td>6.00 m-m</td>
<td>4.74 m-m</td>
</tr>
<tr>
<td>Relocation Cost</td>
<td>$ 1.82</td>
<td>0.09</td>
<td>1.64</td>
<td>-</td>
<td>1.82</td>
<td>1.82</td>
<td>$ 1.44</td>
</tr>
<tr>
<td>Per foot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal</td>
<td>6.00 m-m</td>
<td>6.60 m-m</td>
<td>6.00 m-m</td>
<td>-</td>
<td>6.00 m-m</td>
<td>6.00 m-m</td>
<td>6.12 m-m</td>
</tr>
<tr>
<td>Remove Cost</td>
<td>$ 1.82</td>
<td>2.00</td>
<td>1.82</td>
<td>-</td>
<td>1.82</td>
<td>1.82</td>
<td>$ 1.86</td>
</tr>
<tr>
<td>Per Foot</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport Per Ft/Mile</td>
<td>$ 0.15</td>
<td>1.20</td>
<td>1.31</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>$ 0.45</td>
</tr>
<tr>
<td>Fabricate Cost/Ft</td>
<td>$20.00</td>
<td>13.30</td>
<td>13.80</td>
<td>21.00</td>
<td>15.00</td>
<td>16.50</td>
<td>$16.60</td>
</tr>
<tr>
<td>Install Cost/Ft</td>
<td>$ 2.50</td>
<td>4.90</td>
<td>2.04</td>
<td>2.00</td>
<td>0.65</td>
<td>1.00</td>
<td>$ 2.18</td>
</tr>
<tr>
<td>Relocate Cost/Ft</td>
<td>$ 2.50</td>
<td>9.81</td>
<td>2.39</td>
<td>7.00</td>
<td>0.65</td>
<td>1.00</td>
<td>$ 3.89</td>
</tr>
<tr>
<td>Remove Cost/Ft</td>
<td>$ 6.60</td>
<td>6.39</td>
<td>2.41</td>
<td>11.50</td>
<td>0.85</td>
<td>2.25</td>
<td>$ 5.00</td>
</tr>
</tbody>
</table>
(1) special traffic control or diversion (not costed here)
(2) pickup of replacement sections from the depot
(3) transportation of sections to the construction site
(4) removal of damaged sections to a position nearby original position
(5) offload of sections and placement in original barrier
(6) pickup of damaged sections or debris
(7) transport of damaged sections to depot or other disposal

It was further assumed, as for the analyses in previous sections of this section that the depot is less than 10 miles from the site. Flatbed trailer capacities and load limits will permit four 30 ft sections to be transported, four 20 ft sections, or twelve 10 ft sections.

A "cherry-picker" crane was assumed to go with transport trucks to the depot or meet them there to load sections, although a forklift truck could also serve at the depot. After loading the needed sections, both the crane and the flatbed truck-trailers proceed to the construction site. It was further assumed that sufficient trucks would be requisitioned to accomplish the maintenance activity in one trip from the depot to the site and return. The handling crew for attaching lift cables and maneuvering the PCB's into place was assumed to ride to the depot in some fashion (perhaps the supervisor took them) but to ride back to the site after loading the sections in the truck(s).

It was finally assumed that equipment would have to be paid for in four-hour (half-day) increments.

In order to cost the effort required to replace sections, it is necessary to consider how many sections at most might need to be replaced at a site as a result of a collision. The dynamic and structural analysis presented in Appendix C or D provides an estimate of number of sections that would be damaged in absorbing varying levels of energy as a function of joint design. If the conservative assumption is made that a damaged section must be replaced, it is possible to arrive at some conclusions as to amounts of time and numbers of trucks that would be required as a maximum. Table 27 provides these estimates of number of sections damaged as a result of levels of collision energy ranging from 20.4 to 322 kip-ft (27.7 to 437 kN-m). An examination of this table reveals that no more than one truck would be required for repair of barriers hit with energy levels no greater than Level 3. These data lead directly to Table 28, which presents the cost breakdown
Table 27. Damage Estimates

<table>
<thead>
<tr>
<th>Barrier Connection Type</th>
<th>Section Length (ft)</th>
<th>4500/15/45 Level A *20.4 K-ft</th>
<th>4500/15/60 Level 1 36.5 K-ft</th>
<th>4500/25/60 Level 2A 97.3 K-ft</th>
<th>40,000/15/60 Level 3 322 K-ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Tongue &amp; Groove</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
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<td>C2 Dowell</td>
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<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<tr>
<td>C3 Grid Slot</td>
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<td>2</td>
<td>4</td>
<td>8</td>
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<td></td>
<td>20</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
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<td>3</td>
</tr>
<tr>
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<td>4</td>
<td>8</td>
</tr>
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<td></td>
<td>20</td>
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<td>1</td>
<td>2</td>
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<td>3</td>
</tr>
<tr>
<td>C5 Lapped Joint</td>
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<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>20</td>
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<td>1</td>
<td>2</td>
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</tr>
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<td></td>
<td>30</td>
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<td>1</td>
<td>2</td>
<td>3</td>
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<td>3</td>
</tr>
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<td>1</td>
<td>3</td>
</tr>
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<td>0</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

*Number Sections Damaged

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### Table 28. Cost Bases

#### Sections to Haul

<table>
<thead>
<tr>
<th>Sections to Haul</th>
<th>≤4-30'</th>
<th>5-8 - 30'</th>
<th>6-20'</th>
<th>7-12 - 20'</th>
<th>≤12-10'</th>
<th>13-24-10'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck Use</td>
<td>42.00</td>
<td>84.00</td>
<td>22.00</td>
<td>44.00</td>
<td>69.32</td>
<td>138.64</td>
</tr>
<tr>
<td>Truck OPS Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>133.32</td>
<td>266.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Drivers @ $17.33/hr.
Truck Use @ $42/½ day
Truck OPS @ $22/½ day

#### CRANE COSTS

- Operator: 21.50/hr X 4 = 86.00
- Cherry Picker: 165.00 for 4 hours = 165.00
- Total: $251.00

Plus transport to site and back to depot
Assume same as truck OPS cost: 22.00
- Total: $283.00

#### PICKUP & PLACEMENT COSTS

- Time Base: Empty transport to depot @ 20MPH = 30 min.
- Transport to site @ 20MPH = 30 min.

- 2-Handlers - 1 hour in transit @ 16.54 = $33.08
- Can handle 4 30' (no faster to do 20's or 10's) in 10 minutes
- So: MAX time at site 1 hour @ 16.54 = $33.08

#### DAMAGED SECTIONS - Transp. to depot @ 20 MPH = 30 min.
- Back haul & drop @ 20 MPH = 30 min.

- So: 2 hours just for xport
- Handlers: 3 hours total X 2 X 16.54 = $99.24
- Plus a super for 4 hours @ 21.50 = 86.00
- Total: $185.24

---

**So:**

<table>
<thead>
<tr>
<th>1 TRUCK</th>
<th>2 TRUCKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>133.32</td>
<td>266.00</td>
</tr>
<tr>
<td>283.00</td>
<td>283.00</td>
</tr>
<tr>
<td>99.24</td>
<td>99.24</td>
</tr>
<tr>
<td>86.00</td>
<td>86.00</td>
</tr>
<tr>
<td>$601.56</td>
<td>$734.00</td>
</tr>
</tbody>
</table>

Only differential cost then is joint hookup. (Negligible)

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for a half-day maintenance activity (it could hardly be less, as the table shows) which basically involves men and equipment tied up for that length of time and the costs associated with such an activity. Since no cases involved more than one transport flatbed truck, a flat rate of $602 was taken for the cost of the maintenance activity associated with a single collision. If it is assumed that these sections must be replaced, then the cost associated with that replacement must be taken into account in estimating the total cost of maintenance. For the small numbers of joints that must be fastened in such maintenance jobs, the cost of that operation can be safely neglected. The per-section fabrication costs for each concept presented in Table 14, multiplied by the number of sections expected to be damaged in Table 27, plus $602 was taken for the cost of the maintenance activity associated with a single collision (Table 29). In this table, the total costs for a collision at a given level are presented for each joint concept for each of three section lengths, 10, 20 and 30 ft. In order to present these estimates in a perhaps more meaningful way, Figures 116 through 125 plot a curve for each section length of cost as a function of energy level of collision.

Most of these curves look much the same, with the exception of C1--Tongue and Groove, and C10--Welsbach, but even there, there is a convergence of costs for higher energy collisions, for 10 vs. 20 vs. 30 ft sections. Shorter sections maintain a cost advantage as far as maintenance and replacements costs over longer sections at a given level of energy for most concepts until the higher energy ranges are reached. Note that costs accelerate very rapidly for the lower two levels of energy.

A Hypothetical Case for PCB Cost Analysis

The foregoing section presents a picture of the costs associated with a collision, but the construction engineer needs a more complete perspective of the total costs that he is facing in using PCB for protection of a construction site; that is, cost of the barrier itself, costs for installation, and costs for maintaining the barrier once in place at any given place in his site for a period of time. How many collisions should he expect, and what will the consequences of these be on his total cost picture for construction protection?

In order to illustrate how such a costing estimate might be done, recourse was made to the AASHTO Guide, "Guide for Selecting, Locating, and
<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>SECTION LENGTH</th>
<th>A</th>
<th>1</th>
<th>2A</th>
<th>3</th>
<th>JOINT ASSY</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Tongue &amp; Groove</td>
<td>10</td>
<td>765</td>
<td>928</td>
<td>1254</td>
<td>1906*</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>925</td>
<td>1248</td>
<td>1571</td>
<td>1894*</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1085</td>
<td>1568</td>
<td>1568</td>
<td>2051*</td>
<td>0</td>
</tr>
<tr>
<td>C2 Dowel</td>
<td>10</td>
<td>766</td>
<td>930</td>
<td>1258</td>
<td>1914**</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>926</td>
<td>1250</td>
<td>1574</td>
<td>1898**</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1086</td>
<td>1570</td>
<td>1570</td>
<td>2054**</td>
<td>0</td>
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<tr>
<td>C3 Grid Slot</td>
<td>10</td>
<td>769</td>
<td>936</td>
<td>1270</td>
<td>1938</td>
<td>.03</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>929</td>
<td>1256</td>
<td>1585</td>
<td>1910</td>
<td>.03</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1089</td>
<td>1576</td>
<td>1576</td>
<td>2063</td>
<td>.03</td>
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<tr>
<td>C4 Top T-Lock</td>
<td>10</td>
<td>0</td>
<td>775</td>
<td>1294</td>
<td>1986</td>
<td>.11</td>
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<td></td>
<td>20</td>
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<td>935</td>
<td>1268</td>
<td>1934</td>
<td>.11</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>1098</td>
<td>1594</td>
<td>2090</td>
<td>.11</td>
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<tr>
<td>C5 Lapped Joint</td>
<td>10</td>
<td>772</td>
<td>772</td>
<td>1282</td>
<td>1962</td>
<td>.17</td>
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<tr>
<td></td>
<td>20</td>
<td>932</td>
<td>932</td>
<td>1262</td>
<td>1922</td>
<td>.17</td>
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<tr>
<td></td>
<td>30</td>
<td>1091</td>
<td>1091</td>
<td>1582</td>
<td>2072</td>
<td>.17</td>
</tr>
<tr>
<td>C6 Pin and Rebar</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>964</td>
<td>2050</td>
<td>.55</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>1284</td>
<td>1966</td>
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<td></td>
<td>30</td>
<td>0</td>
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<td>1103</td>
<td>2105</td>
<td>.55</td>
</tr>
<tr>
<td>C7 Vert I-Beam</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>2194</td>
<td>.03</td>
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<td></td>
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<td>2038</td>
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<tr>
<td></td>
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<td>0</td>
<td>1121</td>
<td>2159</td>
<td>.03</td>
</tr>
<tr>
<td>C8 Bottom T-Lock</td>
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<td>0</td>
<td>0</td>
<td>998</td>
<td>2186</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>1318</td>
<td>2034</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>1120</td>
<td>2156</td>
<td>0</td>
</tr>
<tr>
<td>C9 Channel Splice</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1032</td>
<td>2322</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>1352</td>
<td>2102</td>
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<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>1169</td>
<td>2302</td>
<td>2.00</td>
</tr>
<tr>
<td>C10 Welsbach</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1096</td>
<td>2084**</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>1416</td>
<td>1823**</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1736**</td>
<td>0</td>
</tr>
</tbody>
</table>

*May require moving undamaged PCB's to reconnect.

**Will require moving undamaged PCB's.
Figure 116. Barrier Maintenance Cost vs. Energy in Collisions--Cl Tongue and Groove.
Figure 117. Barrier Maintenance Cost vs. Energy in Collisions--C2 Dowel.
BARRIER MAINTENANCE COST VS. ENERGY IN COLLISIONS

Figure 118. Barrier Maintenance Cost vs. Energy in Collisions--C3 Grid Slot.
Figure 119. Barrier Maintenance Cost vs. Energy in Collisions--C4 Top T-Lock.
Figure 120. Barrier Maintenance Cost vs. Energy in Collisions--C5 Lapped Joint.
BARRIER MAINTENANCE COST VS. ENERGY IN COLLISIONS

Figure 121. Barrier Maintenance Cost vs. Energy in Collisions--C6 Pin and Rebar.
Figure 122. Barrier Maintenance Cost vs. Energy in Collisions—C7 Vertical I-Beam.
BARRIER MAINTENANCE COST VS. ENERGY IN COLLISIONS

Figure 123. Barrier Maintenance Cost vs. Energy in Collisions—C8 Bottom T-Lock.
Figure 124. Barrier Maintenance Cost vs. Energy in Collisions--C9 Channel Splice.
Figure 125. Barrier Maintenance Cost vs. Energy in Collisions--Cl0 Welsbach.
Designing Traffic Barrier"(13). The model in Section VII of the guide provides an estimate of collision frequency per year, given certain parameters about the highway and its geometrics with respect to a barrier or obstacle. This is to say,

\[ A = \text{lateral placement from EOP of PCB line} \]
\[ L = \text{length of barrier array} \]
\[ W = \text{width of barrier} \]
\[ \text{ADT} = 2\text{-way volume flow} \]
\[ E_f = \text{vehicle encroachments per mile per year} \]
\[ Y = \text{lateral displacement of encroaching vehicle measured from edge of travelled way to longitudinal face of the barrier} \]
\[ P\{y > A\} = \text{probability of vehicle lateral displacement greater than some value} \]
\[ J = \text{no. of 1 ft increments of width of barrier, i.e. a 2 ft wide barrier would have a J-value of 2.} \]

Obtain estimate of collision frequency per year \( C_f \).

\[
C_f = \frac{E_f}{10560} \cdot (L + 62.9) \cdot P\{Y > A\} +
\]
\[
5.14 \sum_{u} P\{Y > A + 6.0 + \frac{2J-1}{2}\}
\]

Let us now adapt an actual site in Texas for the purpose of demonstrating this approach to cost analysis.

**PLACE:** Stemmons Fwy. I-35

w side of Dallas, Texas

**ADT:** 200,000 for all 8 lanes, divided median

**A:** 3 ft

**L:** 5,000 ft

**W:** 2.3 ft

**P\{Y > A\}:** 98%

**E_f:** 40%
\[ C_f = \frac{E_f}{10560} \cdot (L+62.9) \cdot P \left[ Y > A \right] + 5.14 \sum_{j=1}^{\omega} P \left[ Y > A + 6 + \frac{2v-1}{2} \right] \]

\[ = \frac{40}{10560} \cdot (5000+62.9) \cdot 0.98 + 5.14 \left[ 0.935 + 0.925 \right] \]

\[ \text{if } j=2; \quad P \left[ Y > 3 + 6 + \frac{2-1}{2} \right] = P \left[ Y > 9.5 = 93.5 \right] \]

\[ P \left[ Y > 3 + 6 + \frac{4-1}{2} \right] = P \left[ Y > 10.5 = 92.5 \right] \]

\[ = 0.004 \left[ 4961.6 + 9.56 \right] = 19.88 \text{ collisions per year} \]

or approximately 20

Vehicle Mix:

- Heavy Vehicles 16% 3.2 per year
- Passenger Cars 84% 16.8 per year

Period of time barrier will be in place during construction: 1 Year

Since encroaching vehicles are "selected" randomly and might be distributed approximately normally, a good method of roughly estimating the energy of collision with the barrier might be the mean of energies associated with passenger vehicles at various speeds and angles of encroachment. This would be the mean of levels A, 1, and 2A, or 51.4 kip-ft.

By a similar argument, small trucks at 60 mph and 25 degrees encroachment expend the same energy as larger trucks at lower speeds/angle combinations, and distribute up to the extreme of 40,000 lb vehicles impacting at 15 degrees at 60 mph (322 kip-ft). An estimator of the energy associated with truck collisions would thus be the mean of level 2A and 3, which is 209.7 kip-ft.

Suppose (as was the case in this real-life example) the resident engineer is considering the C-3--Grid-Slot concept, but his contractor can supply the C-5--Lapped Joint. Which should be used on this busy freeway, and which length, 10, 20, or 30 ft?

For C3, the costs of maintenance for 1 year would be:

<table>
<thead>
<tr>
<th>Length</th>
<th>Passenger Car Levels</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ft</td>
<td>($992 \times 16.8)</td>
<td>+ ($1604 \times 3.2) = $21798</td>
</tr>
<tr>
<td>20 ft</td>
<td>($1257 \times 16.8)</td>
<td>+ ($1748 \times 3.2) = $26942</td>
</tr>
<tr>
<td>30 ft</td>
<td>($1413 \times 16.8)</td>
<td>+ ($1820 \times 3.2) = $29562</td>
</tr>
</tbody>
</table>
For C5 the costs would be:

For the 10 ft section:
- Fabricate: $(942 \times 16.8) + (1622 \times 3.2) = \$21016$
- Install: $(1042 \times 16.8) + (1592 \times 3.2) = \$22600$
- Maintain: $(1255 \times 16.8) + (1827 \times 3.2) = \$26930$

From a maintenance standpoint, a 10 ft C5 is the most attractive in this example, however installation costs and relocation costs must also be considered from the previous sections. 5,000 ft of 10 ft C5 would cost:

- Fabricate: $17.00/ft \times 5000 = \$85,000$
- Install: $1.40/ft \times 5000 = \$7,000$
- Maintain: $21,016$

**TOTAL COST** $113,016$

whereas 30 ft sections of C5 would be:

- Fabricate: $16.33 \times 5000 = \$81,650$
- Install: $1.19 \times 5000 = \$5,950$
- Maintain: $29,562$

**TOTAL COST** $117,160$

The much simpler C3 concept, in comparison for 10 ft lengths would cost:

- Fabricate: $16.70/ft \times 5000 = \$83,500$
- Install: $1.41/ft \times 5000 = \$7,050$
- Maintain: $21,798$

**TOTAL COST** $112,348$

30 ft lengths would cost:

- Fabricate: $16.23/ft \times 5000 = \$81,150$
- Install: $1.21/ft \times 5000 = \$6,050$
- Maintain: $29,564$

**TOTAL COST** $116,764$

This rationale can be generalized into a summary table, Table 30, which assumes the nominal vehicle mix on the nation's highways of 16 per cent heavy truck, and 84 percent passenger or similarly sized vehicles. As a matter of determining how sensitive the relative total costs are to vehicle mix, the vehicle mix ratio was changed from 16-84 to 50-50 (an extremely high ratio of trucks, really unrealistic) and Table 31 was generated. Then from these figures, the histogram of Figure 126 was constructed showing the ten least
Table 30. Total 1 Year Costs With Maintenance for Trucks 16% - Passenger Cars 84%.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Length</th>
<th>Fabricate</th>
<th>Install</th>
<th>Level A</th>
<th>Level 1</th>
<th>Level 2A</th>
<th>Level 3</th>
<th>Main Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Tongue</td>
<td>10</td>
<td>$81,500</td>
<td>$6,900</td>
<td>$765</td>
<td>$928</td>
<td>$1,254</td>
<td>$1,906</td>
<td>$21,559</td>
<td>$109,959</td>
</tr>
<tr>
<td>C1 Tongue</td>
<td>20</td>
<td>80,750</td>
<td>6,400</td>
<td>925</td>
<td>1,248</td>
<td>1,571</td>
<td>1,894</td>
<td>26,510</td>
<td>113,660</td>
</tr>
<tr>
<td>C1 Tongue</td>
<td>30</td>
<td>80,900</td>
<td>6,500</td>
<td>1,085</td>
<td>1,568</td>
<td>2,051</td>
<td>29,428</td>
<td>116,228</td>
<td>110,518</td>
</tr>
<tr>
<td>C2 Dowel</td>
<td>10</td>
<td>82,000</td>
<td>6,900</td>
<td>766</td>
<td>930</td>
<td>1,258</td>
<td>1,914</td>
<td>21,618</td>
<td>116,014</td>
</tr>
<tr>
<td>C2 Dowel</td>
<td>20</td>
<td>81,000</td>
<td>6,400</td>
<td>926</td>
<td>1,250</td>
<td>1,574</td>
<td>1,898</td>
<td>26,555</td>
<td>113,955</td>
</tr>
<tr>
<td>C2 Dowel</td>
<td>30</td>
<td>80,650</td>
<td>5,900</td>
<td>1,086</td>
<td>1,570</td>
<td>2,054</td>
<td>29,464</td>
<td>116,014</td>
<td>116,014</td>
</tr>
<tr>
<td>C3 Grid</td>
<td>10</td>
<td>83,500</td>
<td>7,050</td>
<td>769</td>
<td>936</td>
<td>1,270</td>
<td>1,938</td>
<td>21,793</td>
<td>112,343</td>
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<tr>
<td>C3 Grid</td>
<td>20</td>
<td>81,750</td>
<td>6,550</td>
<td>929</td>
<td>1,256</td>
<td>1,585</td>
<td>1,910</td>
<td>26,704</td>
<td>115,004</td>
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<tr>
<td>C3 Grid</td>
<td>30</td>
<td>81,150</td>
<td>6,050</td>
<td>1,089</td>
<td>1,576</td>
<td>1,576</td>
<td>2,063</td>
<td>29,572</td>
<td>116,772</td>
</tr>
<tr>
<td>C4 Top T</td>
<td>10</td>
<td>86,500</td>
<td>7,100</td>
<td>0</td>
<td>775</td>
<td>1,294</td>
<td>1,986</td>
<td>16,834</td>
<td>110,434</td>
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<tr>
<td>C4 Top T</td>
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<td>83,250</td>
<td>6,600</td>
<td>0</td>
<td>935</td>
<td>1,268</td>
<td>1,934</td>
<td>17,460</td>
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<td>82,650</td>
<td>6,050</td>
<td>0</td>
<td>1,098</td>
<td>1,594</td>
<td>2,090</td>
<td>20,970</td>
<td>109,670</td>
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<tr>
<td>C5 Lapped</td>
<td>10</td>
<td>85,000</td>
<td>7,000</td>
<td>772</td>
<td>772</td>
<td>1,282</td>
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<tr>
<td>C5 Lapped</td>
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<td>82,500</td>
<td>6,500</td>
<td>932</td>
<td>932</td>
<td>1,262</td>
<td>1,922</td>
<td>22,600</td>
<td>111,600</td>
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<tr>
<td>C5 Lapped</td>
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<td>81,650</td>
<td>5,950</td>
<td>1,091</td>
<td>1,091</td>
<td>1,582</td>
<td>2,072</td>
<td>26,925</td>
<td>114,525</td>
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<tr>
<td>C6 Vert P</td>
<td>10</td>
<td>90,500</td>
<td>7,350</td>
<td>0</td>
<td>0</td>
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Factor for Trucks = 2.00
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Factor for Trucks = 5.00
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\text{MIX} = 16 - 84 \ \cdots \ \cdots \]

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*Percentage of trucks and passenger cars respectively.

Figure 126. Comparison of Ten Least Expensive PCB Concepts.
expensive concepts for a vehicle mix of 16-84 trucks: cars (realistic) and the worst-case 50-50 mix. All costs, of course, go up for this worst case, but the relative standing of most of the barrier joint concepts for the three lengths of interest do not change a great deal. The least costly concept for both traffic mix cases is the familiar vertical pin with rebar, C6 concept, at a length of 30 ft, with C8, the Bottom T-Lock at 30 ft the next least expensive (tied with C7--Vertical I-Beam) for the heavy truck mix case. Others in the ten least expensive can be seen by studying this figure. Note that the longer lengths predominate in overall costs, and positive joints appear to have an advantage in cost over those less positive, although this relationship is not completely straightforward.

Analyses such as that presented above can be generated for a wide variety of different traffic situations at proposed construction sites to assist the construction engineer in choosing an appropriate design of PCB for his particular needs.
BARRIERS IN CONSTRUCTION ZONES

APPENDIX F

Conceptual Drawings

Prepared for
Contract DOT-FH-11-9458
Office of Research
Federal Highway Administration
U. S. Department of Transportation

Appendix F
by
Project Staff

Texas A&M Research Foundation
Texas Transportation Institute
The Texas A&M University System
April 1985
PLAN VIEW
(Scale: 3/8" = 1'-0"

ELEVATION
(Scale: 3/8" = 1'-0"

SECTION 'A-A'
(Scale: 1/2" = 1'-0"

APR, '90 - D. GRAVES AS NOTED

RECYCLED
PRESTRESSED CONCRETE BEAM
Each channel is formed from a 3" x 10" x 1/4" plate.

Fill, sand, or gravel.

Splice plate.

Compression strut.

Splice plate.

Plan view (Scale: 1/2" = 1'-0")

Elevation (Scale: 1/2" = 1'-0")

Section 'A-A' (Scale: 1/2" = 1'-0")

Section 'B-B' (Scale: 1/2" = 1'-0")
CABLE OR STEEL BANDS

STD. 30' UTILITY POLE (WOOD)

USED TIRE STACKS

PLAN VIEW
(Scale: 1/2" = 1'-0"

ELEVATION
(Scale: 1/2" = 1'-0"

SECTION 'A-A'
(Scale: 1/2" = 1'-0"

TEXAS A&M UNIVERSITY

FILL, SAND, OR GRAVEL

1/2" O CABLE OR 1/8" STEEL BANDS

POLE BARN
REFERENCES


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