Bending stresses in the transverse frames due to Poisson's ratio effect in a box girder bridge (Rio-Niterói), M.S. thesis, May 1975.

John E. O'Brien
BENDING STRESSES IN THE TRANSVERSE FRAMES DUE TO POISSON'S RATIO EFFECT IN A BOX GIRDER BRIDGE (RIO-NITEROI)

by

John E. O'Brien

A Thesis
Presented to the Graduate Committee of Lehigh University in Candidacy for the Degree of Master of Science in Civil Engineering

FRITZ ENGINEERING LABORATORY LIBRARY

May 1975
This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

\[5/9/75\]

(date)

Professor Alexis Ostapenko

Professor D. A. VanHorn
Chairman
Department of Civil Engineering
ACKNOWLEDGEMENTS

This research project was sponsored by Empresa de Engenharia e Construção de Obras Especiais of Rio de Janeiro, Brazil.

I would especially like to thank Dr. A. Ostapenko, who as my thesis advisor helped me tremendously. Others who were of great help to me are Dr. J. W. Fisher, Dr. G. C. Driscoll, Mr. Hugh Sutherland, and Mr. David DePaoli. I am also grateful to Ms. Joan L. Gorski for typing the manuscript and to the drafting staff for their work.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. INTRODUCTION</td>
<td>3</td>
</tr>
<tr>
<td>1.1 History</td>
<td>3</td>
</tr>
<tr>
<td>1.2 Reasons for Field Investigation</td>
<td>4</td>
</tr>
<tr>
<td>1.3 Construction Procedure</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Number and Type of Gages</td>
<td>6</td>
</tr>
<tr>
<td>1.5 Scope of Thesis</td>
<td>7</td>
</tr>
<tr>
<td>2. INSTRUMENTATION AND DATA REDUCTION</td>
<td>8</td>
</tr>
<tr>
<td>3. TRANSVERSE STRESS ANALYSIS</td>
<td>10</td>
</tr>
<tr>
<td>3.1 Observed Strain Patterns and Possible Causes</td>
<td>10</td>
</tr>
<tr>
<td>3.2 Reason for Analysis</td>
<td>10</td>
</tr>
<tr>
<td>3.3 Assumptions</td>
<td>11</td>
</tr>
<tr>
<td>3.4 Approach to Analysis</td>
<td>11</td>
</tr>
<tr>
<td>3.5 Force Method</td>
<td>13</td>
</tr>
<tr>
<td>3.6 Calculation of Strain</td>
<td>18</td>
</tr>
<tr>
<td>3.7 Calculation of Stress</td>
<td>18</td>
</tr>
<tr>
<td>4. RESULTS</td>
<td>20</td>
</tr>
<tr>
<td>4.1 Initial Results</td>
<td>20</td>
</tr>
<tr>
<td>4.2 Data Smoothening</td>
<td>22</td>
</tr>
<tr>
<td>4.3 Summary</td>
<td>23</td>
</tr>
<tr>
<td>5. RECOMMENDATIONS</td>
<td>24</td>
</tr>
<tr>
<td>5.1 Consideration of Poisson's Effect in Design</td>
<td>24</td>
</tr>
<tr>
<td>5.2 Effective Width for Analysis</td>
<td>24</td>
</tr>
<tr>
<td>TABLES</td>
<td>25</td>
</tr>
<tr>
<td>FIGURES</td>
<td>26</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>41</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>42</td>
</tr>
<tr>
<td>a. Appendix A</td>
<td>50</td>
</tr>
<tr>
<td>b. Appendix A - Tables</td>
<td>50</td>
</tr>
<tr>
<td>c. Appendix A - Figures</td>
<td>51</td>
</tr>
<tr>
<td>d. Appendix B</td>
<td>59</td>
</tr>
<tr>
<td>e. Appendix C</td>
<td>62</td>
</tr>
<tr>
<td>f. Appendix C - Figures</td>
<td>64</td>
</tr>
<tr>
<td>VITA</td>
<td>67</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Effective Widths Computed from Transverse Strains</td>
</tr>
<tr>
<td>A-1</td>
<td>Sequence of Electrical Gage Static Readings</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Construction Sequence</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>Locations of Instrumented Cross Sections in the Rio Side Span</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Transverse Strains at FB27 (Jetties to Pontoon)</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>Transverse Strains at FB42 (Jetties to Pontoon)</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>Transverse Strains at FB27 (Pontoon to Pier Rings)</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Transverse Strains at FB42 (Pontoon to Pier Rings)</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>Transverse Strains at FB27 (Center Span Lift)</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>Transverse Strains at FB42 (Center Span Lift)</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>Flow Chart of Computer Program for the Determination of Effective Widths</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>Model of Typical Transverse Frame for Analysis</td>
<td>35</td>
</tr>
<tr>
<td>11</td>
<td>Cantilever Idealization of Structure for Force Method</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>Moment (M), Shear (S), and Thrust (P) Diagrams for Unit Redundants</td>
<td>37</td>
</tr>
<tr>
<td>13</td>
<td>Secondary Stress Effects</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>Forces Acting on a Cross Section</td>
<td>39</td>
</tr>
<tr>
<td>15</td>
<td>Revised Model of Typical Transverse Frame for Analysis</td>
<td>40</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

(continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>Position of Test Loads in February 1974 (Convoy of 21 17.5 Ton Trucks)</td>
<td>51</td>
</tr>
<tr>
<td>A-2</td>
<td>Systems of Data Acquisition of the Rio Side Span</td>
<td>52</td>
</tr>
<tr>
<td>A-3</td>
<td>Location of Gages at FB17</td>
<td>53</td>
</tr>
<tr>
<td>A-4</td>
<td>Location of Longitudinal, Rosette, and Temperature Gages at FB27</td>
<td>54</td>
</tr>
<tr>
<td>A-5</td>
<td>Location of Transverse Gages at FB27</td>
<td>55</td>
</tr>
<tr>
<td>A-6</td>
<td>Location of Gages at FB42</td>
<td>56</td>
</tr>
<tr>
<td>A-7</td>
<td>Locations of Gages at FB51</td>
<td>57</td>
</tr>
<tr>
<td>A-8</td>
<td>Locations of Gages at FB57</td>
<td>58</td>
</tr>
<tr>
<td>C-1</td>
<td>Matrix $B_1$, Bar Forces Due to Unit Redundant Forces Applied on the Primary Structure</td>
<td>64</td>
</tr>
<tr>
<td>C-2</td>
<td>Matrix $F$, Total Structure Flexibility Matrix</td>
<td>65</td>
</tr>
<tr>
<td>C-3</td>
<td>Matrix $V$, Deflections at the Ends of the Released Members from Poisson's Effect</td>
<td>66</td>
</tr>
</tbody>
</table>
ABSTRACT

Bending stresses in a box girder lead to a lateral expansion (or contraction) of the flange and web plates due to Poisson's ratio effect. Floor beams and transverse stiffeners inhibit this lateral deformation and thereby cross-bending stresses develop in these transverse components of the girder. Although these stresses may be of substantial magnitude (values as high as 600 kg/cm² have been observed), they have not been considered in design.

A field investigation performed on a steel box girder bridge (the Rio-Niteroi bridge) offered an opportunity to observe this phenomenon. Presented here is a study of the transverse strain readings taken on the floor beams and transverse stiffeners of this bridge. The strains showed well defined patterns of axial force and bending moment distribution. Analysis of these patterns resulted in the determination of the effective plate widths and the stress for the individual transverse components. The effective width for this Poisson's ratio effect was found to be dependent on the length of the component (floor beam and transverse stiffeners), rather than on the plate thickness.

Because of the substantial level of stress resulting from this phenomenon, it is recommended that these stresses should be considered in design of steel box girders. For the analysis of Poisson's ratio effect the following value of effective widths are proposed:
a) For a flange which extends beyond the limits of the box, thus restraining that component, an effective width of 30% of the length should be used.

b) For an unrestrained web or flange an effective width of 19% of the length of the component should be used.
1. INTRODUCTION

1.1 History

In Brazil, the Guanabara Bay separates the cities of Rio de Janeiro (population: five million) and Niteroi (population: four hundred thousand) with a two-kilometer stretch of water at its mouth. Previously, the only ways to commute from one city to the other was to drive 2.5 hours around the bay or to take a ferry. In 1965, after decades of consideration, the Brazilian government decided to build a bridge near the mouth of the bay, directly connecting the two population centers and supplying an important link in the north-south interstate highway.

Even though the two-kilometer stretch of water seemed to be the most logical choice of the bridge site, a 10.2 kilometer stretch further inland was chosen for several reasons. If the two-kilometer site was chosen, the bridge would have exits into heavily populated congested areas, not into the existing highway system, as it does now. Also, at the chosen site, piles for the foundations of the piers had not to be driven as far. Military considerations, as well as the requirements of a nearby airport, were further factors in determining the selected site of the bridge.

A multi-span concrete box girder was found to be the most suitable system for spanning most of this stretch of water. The height limitation imposed by the nearby airport and the head room
and the clear span needed for the shipping channel necessitated that the portion of the bridge across the shipping channel be of the steel box girder type. This three-span continuous section was to have a center span of 300 meters making it the longest clear span for an unstayed box girder in the world.

Because of the magnitude of this project, the Brazilian government created a special bridge authority, ECEX*, to construct the bridge. The function of ECEX was to coordinate and supervise the combined efforts of the many contractors that participated in building this bridge. It was originally intended that ECEX also manage the completed bridge; however, this function was later handed over to the Department of Transportation (DNER-Departamento Nacional de Estradas de Rodagem).

1.2 Reasons for Field Investigation

During the course of this bridge project, four similar box girder bridges failed (Australia, Austria, Germany, and Great Britain). (1)** These failures prompted ECEX to initiate an extensive field investigation of this long-span box girder bridge. As a result, a Lehigh University team was invited to conduct stress

---

*ECEX - Empresa de Construção e Exploração da Ponte Presidente Costa e Silva, later renamed Empresa de Engenharia e Construção de Obras Especiais.

**Numbers in parentheses indicate references listed on page 41.
measurements on the steel portion of the bridge.* The soundness of the bridge under construction loads was of primary importance to ECEX in this investigation. Other areas to be investigated were the behavior under test loads, the assumptions of linear stress and temperature distribution, the load distribution between individual boxes, the secondary stresses in floor beams, and the stress histories due to temperature fluctuations and moving traffic loads.

1.3 Construction Procedure

Several very unique construction techniques were used in the building of the steel portion. Large plate panels of the box girders were fabricated in England; these were then shipped to Brazil where they were assembled into a number of large box sections. The first section assembled was the 4200-ton, 176-meter center section (shown in Figure 1-d). This section (the only one assembled completely on land) was made water-tight so that it could be used as a giant pontoon to aid in the erection of other portions of the bridge. The whole construction sequence is shown in Fig. 1. (2)

The first step was the erection of the 292-meter Niteroi side span (Fig. 1a); it was fabricated as two separate box girders and transported one box at a time on the pontoon to the piers where

*A separate study was conducted on the concrete portion of the bridge by the Laboratorio Nacional de Portugal.
the boxes were set on the pier rings. These pier rings were platforms that surrounded each set of dual pier shafts and provided support for the box girders. Then the rings were jacked to the top of the pier shafts where the separate girders were slid together and welded to form one unit. The Rio side span (the second step) was erected in a similar manner (Fig. 1b). The third step was the erection of the 44 meter steel end span on the Niteroi side (Fig. 1c). This span was fabricated as two separate girders, floated out, and hoisted individually into position. The erection of the center span (the pontoon) was the fourth step (Fig. 1d). This span was jacked up out of the water on four jacking columns suspended from both side spans. In position at the top, it was bolted to the side spans to form a continuous three span structure with a maximum span of 300 meters. The final, fifth, step was the erection of the other 44 meter end span on the Rio side (Fig. 1e).

1.4 Number and Type of Gages

One of the unique aspects of the investigation conducted by the Lehigh team is the extent of the instrumentation. The static tests (listed in Table A-1) employed 357 electrical gages located at the five cross sections of the Rio side span shown in Fig. 2. Of the 357 electrical gages, 305 were strain gages and the remaining 52 were temperature gages. Also, eight scratch gages were installed and mechanical gage readings were taken at 90 locations. Sixty-eight electrical strain gages were installed on the orthotropic deck at FB17 and 42 in order to study the dynamic effects of traffic.
1.5 Scope of Thesis

The study of secondary stresses in the floor beams, vertical web stiffeners, and transverse bottom flange stiffeners (Fig. 3) was one of the areas of this research project which is presented in this thesis. A floor beam and the vertical web and bottom flange stiffeners at the same location comprise a frame; and the study of patterns of strains observed in the direction of such frames during construction was the prime objective of the thesis.

The main part of the text is the description of the analysis of the secondary transverse stresses. These stresses are a result of the resistance of the floor beam frames to the transverse expansion or contraction of the top, web, or bottom plates of the girder due to the Poisson's ratio effect (henceforth, called Poisson's effect) from the stresses in the longitudinal direction of the girder.

Results of this study indicate the level of the secondary stresses and give the values of effective width of the plates participating in the action of the transverse frames. In conclusion, recommendations are made for possible use in design of similar box girder bridges. A brief discussion of the instrumentation and data reduction is included in the text so that the scope of this study may be more clearly understood. A more detailed description of instrumentation and data reduction is presented in the Appendices.
2. INSTRUMENTATION AND DATA REDUCTION

All of the strain readings analyzed in this report were taken with electric strain gages. Of the five instrumented cross sections of the Rio side span (Fig. 2), two cross sections (FB27 and FB42) were chosen to place gages in the transverse direction of the frame. This choice was made primarily because FB27 was a typically braced section and FB42 was a typically unbraced section; other reasons are given in the detailed description of the instrumentation in Appendix A. The transverse gages were placed on the plate and on the flange of the transverse frames at the ends of the members near the joints in order to define the moment distribution in them.

During the movement of the north box of the Rio side span from the jetties to the pontoon and from the pontoon to the pier rings, strain readings were taken with a Budd Digital Strain Indicator.* All subsequent readings were taken with a B&F Multi-Channel Digital Strain Indicator** in conjunction with a teletype. Henceforth, these two data acquisition devices shall be referred to as Datran and B&F, respectively.

* Budd Model A-110
** B&F Instruments Model SY 161-100-U
In order that a computer analysis could be performed, all the readings were transferred onto computer cards. Appropriate computer programs (depending on the type of study) were used to calculate stresses, strains, and temperatures. As a final step before detailed analysis, these results were plotted on sample cross-sections. See Appendix B for a more detailed description of this process.
3. TRANSVERSE STRESS ANALYSIS

3.1 Observed Strain Patterns and Possible Causes

Figure 3 (transverse strain changes at FB27 during the transfer from jetties to pontoon) shows a pattern across the member cross sections of large strains of the same sign, but of varying magnitude. This pattern indicates the presence of moment and axial force despite the absence of vertical loads. Similar patterns are also shown in Figs. 4 to 8 for FB42 and for other cases of loading. These strains could not have been caused by temperature effects; for example in the case of Fig. 5 both readings were taken at night when the variation in temperature was less than 2°C at any point in the frame. The only other explanation was Poisson's effect.

Poisson's effect occurs when large changes in strain in the longitudinal direction attempt to create a corresponding opposite transverse strain in the plates of the girder. This tendency for shrinkage or expansion (equivalent to 30% of the longitudinal strain) is resisted by the floor beams and stiffeners and thereby the patterns of moment and axial force observed in the transverse frames are created.

3.2 Reason for Analysis

Figures 3 to 8 (6 cases of data) show many consistent strain readings with a magnitude of up to 300 micro-cm/cm (equiva-
lent to 600 kg/cm$^2$). These strains offer an opportunity to investigate this phenomenon since proper understanding of Poisson's effect is important for evaluation of possible stress levels in a realistic analysis and design of similar bridge structures. This data can also serve as a tool for establishing the values of effective widths in stiffened plates affected by Poisson's effect.

3.3 **Assumptions**

In order to analyze these transverse frames the following assumptions were made:

1. The effective width is constant over the length of each frame member.
2. The two vertical members have the same constant effect width.
3. The gross normal stress varies linearly from top to bottom of the box girder.

Thus, there are three unknown effective widths.

3.4 **Approach to Analysis**

Since any method of indeterminate analysis can only handle as many unknowns as there are redundants and the three unknown effective widths add three more unknowns, the problem is impossible to solve directly. The additional needed relationships are established by utilizing the transverse strain readings.
The solution to this problem comes from the requirement that at the correct values for the effective widths, the strains calculated at the points of measurement should be as close as possible to the measured values. Thus, the process consists of minimizing the error between the calculated and measured strains. This minimization is started by assuming some random values for the three effective widths (effective widths of the top, vertical, and bottom members).

Using the initial random effective widths, the strains due to Poisson's effect on the frame are calculated at the points of measurement using the force method. Then, the error is computed as the sum of squared differences between the calculated and the measured strains. Next, the effective width for the top member is increased by a certain increment and the analysis repeated giving a new value of the error. If the new error is less or equal to the previous error, the effective width of the top member is changed to the incremented value and the effective width of the vertical member is then incremented. If the new error is greater than the previous error, the previous effective width of the top member is decreased by the increment and a new error calculated. If the new error is still not less or equal to the value of the error for the unincremented effective width for the top member, the unincremented effective width for the top member is kept and then the effective width for the vertical member is incremented. When this process is completed with the effective width of the vertical
member, the effective width of the bottom member is incremented and then the process is returned back to the effective width for the top member. This technique if repeated over and over until the error cannot be decreased any more.

With these final effective widths values, stresses can be obtained at various points in the frame. Figure 9 is the general flow chart of the computer program that performs this process of calculating effective widths and corresponding stresses. By solving all six cases of data in the same manner (Figs. 3 to 8), the resultant effective width values can be compared and appropriate conclusions drawn.

3.5 Force Method

The force method was chosen for analyzing the transverse frames primarily because of its ability to handle any of the six sets of data with very little modification. (3) Another important reason for the selection was that the matrix form of the force method was very suitable for the available computer (CDC 6400).

The first step in the analysis of a transverse frame in the box girders is to decide on the primary structure and redundants of the frame as shown in Fig. 10 for a cross section of the completed bridge (5 redundants). In this primary structure, the frame can be represented as a series of cantilevers (Fig. 11). Each of the cantilevers has a moment, a shear, and an axial force acting as its
free end, denoted by M, S, and P, respectively. These bar forces are listed in order of member number, and sublisted in order of M, S, and P. The sign convention is indicated by the positive directions shown in Fig. 11. This model can be readily modified to represent a single box case by eliminating redundants 4 and 5.

The elements for the S matrix are found from

\[ S = (B_0)R + (B_1)X \]  

(1)

where:

- \( R \) = matrix of external loads applied to the nodal points.
- \( X \) = matrix of the values of redundants.
- \( B_0 \) = matrix of bar forces due to real external loads on the primary structure.
- \( B_1 \) = matrix of bar forces due to unit redundant forces applied on the primary structure.

Since the internal forces of the frame are a result of Poisson's effect only, \( R \) matrix equals zero. Consequently, Eq. 1 reduces to

\[ S = (B_1)X \]  

(2)

The values of the redundants are found from the matrix equation

\[ X = -[(B_1)^T \cdot F \cdot B_1]^{-1} \cdot (B_1)^T \cdot V \]  

(3)

where the additional notation is

- \( V \) = deflections created at the end of each cantilever by Poisson's effect on that released member.
- \( F \) = total flexibility matrix.
The total flexibility matrix $F$ of a structure is composed of basic element flexibility matrices ($f_i$), one for each member. For a cantilever the basic element flexibility matrix is

$$ f_i = \begin{bmatrix} \frac{L_i}{EI_i} & \frac{L_i^2}{EI_i} & 0 \\ \frac{-L_i^2}{EI_i} & \frac{L_i^3}{EI_i} & 0 \\ 0 & 0 & \frac{L_i}{EA_i} \end{bmatrix} $$

where:

$L_i$ = length of the $i^{th}$ member.

$A_i$ = area of the $i^{th}$ member.

$I_i$ = moment of inertia of the $i^{th}$ member.

$E_i$ = modulus of elasticity.

The total flexibility matrix $F$ is shown in Fig. C-2 of Appendix C.

The derivation of the $B_1$ matrix is facilitated by drawing the $M$, $S$, and $P$ diagrams for the redundants of unit value applied on the primary structure (Fig. 12). Then, the elements of the $B_1$ matrix are found as the forces on the ends of the released cantilevers. The complete $B_1$ matrix is shown in Fig. C-1 of Appendix C.

The derivation of the $V$ matrix is facilitated by drawing the longitudinal stress, deflected shape, basic curvature, and
basic axial strain diagrams for the primary structure due to Poisson's effect (Fig. 13). In this derivation, the first things that need to be known are the changes in transverse strain in the top and bottom flange plates of the box girder as if the plates were unstiffened. These changes are found from the longitudinal stress in the respective flanges ($\sigma_T$ and $\sigma_B$), as follows:

for the top flange:

$$\varepsilon_T = (-0.3)\sigma_T/E$$

(5a)

for the bottom flange:

$$\varepsilon_B = (-0.3)\sigma_B/E$$

(5b)

The corresponding strains in the web plates are just a linear variation from $\varepsilon_T$ to $\varepsilon_B$.

The axial strain and curvature in the primary structure are found from the following equations:

The axial strain in the floor beam

$$\varepsilon_t = \varepsilon_T \cdot t_t \cdot \frac{b_t}{A_t}$$

(6a)

The curvature in the floor beam

$$\phi_t = \varepsilon_t \cdot \frac{2t_t}{I_t}$$

(6b)

The axial strain in the bottom stiffeners

$$\varepsilon_b = \varepsilon_B \cdot t_t \cdot \frac{b_b}{A_b}$$

(6c)

The curvature in the bottom stiffeners

$$\phi_b = \varepsilon_b \cdot \frac{2t_t}{I_b}$$

(6d)

The axial strain at the top of the vertical stiffeners

$$\varepsilon_vt = \varepsilon_T \cdot t_v \cdot \frac{b_v}{A_v}$$

(6e)
The curvature at the top of the vertical stiffeners
\[ \nu_t = \nu_v \cdot e_v \cdot A_v / I_v \]  
(6f)

The axial strain at the bottom of the vertical stiffeners
\[ \nu_b = B \cdot t_v \cdot b_{ev} / A_v \]  
(6g)

The curvature at the bottom of the vertical stiffeners*
\[ \nu_b = \nu_v \cdot e_v \cdot A_v / I_v \]  
(6h)

In the above expressions, \( t_t, t_v, t_b \), are the thickness of the top, vertical, and bottom plates of the girder respectively. \( b_{et}, b_{ev}, b_{eb} \) are the effective widths of the top, vertical, and bottom plates of the girder respectively. \( e_t, e_v, e_b \) are the eccentricities from the center of the plate of the top, vertical, and bottom members of the frame to their respective centroidal axes. \( A_t, A_v, A_b \) are the areas of the top, vertical and bottom members of the frame. \( I_t, I_v, I_b \) are the moments of inertia of the top, vertical, and bottom members of the frame.

The \( V \) matrix is thus calculated by finding the deflections at the end of each released cantilever element due to these strains and curvatures (See Appendix C for the details of calculations).

Once the \( B, F, \) and \( V \) matrices have been computed, the redundants can be solved using Eq. 3. Then the member bar forces (\( S \) matrix) are obtained from Eq. 2.

*Values of the axial strains and curvatures between the top and bottom of the vertical stiffeners have a linear variation.
3.6 Calculation of Strain

The strains at the points of measurements are computed from the forces in the S matrix. These are the calculated strains that are compared to the measured strains in Section 3.4. The calculated strains ($\varepsilon_c$) are equal to the sum of the strain produced by the redundants ($\varepsilon_R$) and the strain produced by Poisson's effect on the primary structure ($\varepsilon_P$). The equations to find $\varepsilon_R$ and $\varepsilon_P$ are

$$\varepsilon_R = \frac{P}{AE} + \frac{M \cdot c}{I \cdot E}$$  \hspace{2cm} (7)

$$\varepsilon_P = \varepsilon + \phi \cdot c$$  \hspace{2cm} (8)

where for a particular point M and P are the moment and thrust created by the redundants, A and I are the area and moment of inertia for the particular member, c is the distance from the centroidal axis, E is the modulus of elasticity, and $\varepsilon$ and $\phi$ are the axial strain and curvature calculated in Eqs. 6.

3.7 Calculation of Stress

Once the final effective widths are found by the error minimization process described in Section 3.5, the stresses can be calculated. Even though the strains across the depth of a member must be linear and continuous the stresses are linear but not continuous. There are three places in the cross section where the stresses reach local maxima:
\( \sigma_1 \) in the exterior fiber of the plate,
\( \sigma_2 \) in the web of the member at the plate interface,
\( \sigma_3 \) in the flange of the floor beam or stiffener.

The stress across the cross section is a function of three effects as shown in Fig. 14. The stress required to restrain the top flange from Poisson's effect \((-P_p/A_f)\), the stress from Poisson's effect on the released member \((P_p/A + \frac{M_p}{I})\), and the stress created by the redundants \((P_R/A + \frac{(S_R X - M_R c_2)}{I})\). From this the important stresses on the section in question become:

\[
\sigma_1 = -\frac{P_p}{A_f} + \left(\frac{M_p c_1}{I}\right) + \left(\frac{P_R}{A} + \frac{(S_R X - M_R c_2)}{I}\right) \tag{9a}
\]

\[
\sigma_2 = \left(\frac{P_p}{A} - \frac{M_p c_1}{I}\right) + \left(\frac{P_R}{A} + \frac{(S_R X - M_R c_2)}{I}\right) \tag{9b}
\]

\[
\sigma_3 = \left(\frac{P_p}{A} + \frac{M_p c_3}{I}\right) + \left(\frac{P_R}{A} - \frac{(S_R X - M_R c_3)}{I}\right) \tag{9c}
\]

where \( A \) is the total area of the member; \( A_f \) is the effective area of the flange comprised of the plate, and \( x \) is the distance from the free end of the member; \( c_1, c_2, c_3 \) are the distances to the centroidal axis from stress points 1, 2, and 3, respectively. The subscripts \( R \) and \( P \) indicate whether the bar force subscripted \( I \) is from a redundant or from Poisson's effect on the released structure.
4. RESULTS

4.1 Initial Results

The first results from the single box data analyzed using the original model of Chapter 3 (a three-redundant single box), showed a definite trend of the effective width being dependent on the length of a member and independent of the plate thickness. As seen in Table 1, Column 8, the $b_e/L$ ratios for the top members are almost the same for all four cases. Also, the vertical and bottom members both have nearly the same $b_e/L$ ratios, though lower ones than the top members.

The ratios for the vertical members at FB27 are slightly larger than the vertical ratios at FB42. To make the analysis for FB27 more realistic, a new model was introduced (a five-redundant single box, having both braces). The results became even more consistent with those of FB42 (three-redundant) model.

Three different models were tried in the analysis of the data for the center span lift (double box section). The data for both FB27 and FB42 was analyzed using the model of Fig. 10 in Chapter 3 (five-redundant, double box). The data for FB27 was also analyzed using a six-redundant model of Fig. 15 in which both cross braces are considered. The data of FB42 was similarly analyzed in a four-redundant model with cross bracing.
Apparently, because of the errors introduced by instrument drift and voltage fluctuations, the readings for the center span lift (complete structure - double box) gave no conclusive results by any of the analytical models used.

Much of the measured data indicated stresses in the order of 600 kg/cm², and the analytical results from the programs for the single box section showed calculated stresses that were in agreement with these measured values. The effective plate width was found to be $b_e/L = 0.30$ for the top members, and $b_e/L = 0.19$ for the vertical and bottom members. This result, implying that the effective width is a function of length, is based on two observations. Firstly, the top members (the floor beams) at FB27 and FB42 have the same length but different plate thicknesses, 10mm and 16mm, respectively, and the results in Column 8 of Table 1 show that the $b_e/L$ ratios for the top members are essentially the same ($\approx 0.3$) at both FB42 and FB27 despite this large difference in plate thickness. Secondly, the vertical and bottom members, although being of different section properties and lengths, have nearly the same $b_e/L$ ratios ($\approx 0.19$). The difference between the top member value and the vertical and bottom member value seems to be primarily due to the fact that the top flange plate of the girder is cantilevered out, thus restraining the top member from lateral movement.
4.2 Data Smoothening

Data smoothening was tried in order to improve the single box results and to obtain consistent results from the center span lift data. This smoothening was performed by firstly, calculating the strains at the points of measurements, using the obtained values for the effective widths (0.30L for the top member and 0.19L for the vertical and bottom members); secondly, by comparing these calculated strains to the measured strains and eliminating all measured values which disagreed with the calculated values by more than 20%. Thus smoothened data was then run on the original programs and the results are listed in Columns 9 to 11 of Table 1. For the single box data this process was done using the five-redundant FB27 program and the three-redundant FB42 program. For the double box structure smoothening was performed on the six-redundant FB27 program and both the four and five-redundant FB42 programs. The result was that the initial single box observations were confirmed. However, no consistent results could be obtained for the double box structure.

The reason the data from the center span lift gave inconsistent results was apparently the time period between the zero and final readings. One day elapsed between the readings, and this enabled the amplifier of the data acquisition device (B&F) to drift. A noticeable voltage fluctuation during this period may also have contributed to the poor readings.
4.3 Summary

Some of the changes in stresses produced by Poisson's effect in this structure went as high as 600 kg/cm². Being approximately 20% of the yield stress, these stresses could be significant when taken into account with other stresses due to dead load, traffic loads, impact, and wind loads.

In this bridge the governing factor for the effective width was found to be the length of the member. The specific values for the effective widths are \( b_e = 0.19L \) for the vertical and bottom stiffeners, and \( b_e = 0.30L \) for the floor beams. The larger value for the floor beams is due to two reasons: firstly and primarily, the floor beams are restrained on both ends from axial movement by the cantilever flange plate of the girder; secondly, the top flange of the girder is more heavily stiffened in the longitudinal direction than the webs and bottom flange.
5. RECOMMENDATIONS

5.1 Consideration of Poisson's Effect in Design

It is recommended that Poisson's effect should be considered in design of steel box girders. The stresses due to this phenomenon in long span structures with high dead load moment could be significant and should be added to other stresses. Poisson's effect could also increase the possibility of fatigue failure in short span structures with large cyclic moment changes due to live loads.

5.2 Effective Width for Analysis

On the basis of the field observations on the Rio-Niteroi bridge, the following values of effective widths for the analysis of Poisson's effect can be recommended. For the case of a flange plate, which cantilevers beyond the box, the effective width (for the transverse frames) should be 0.3L. For the case of a flange or web plate unrestrained at its edges, a value of 0.19L should be used.
<table>
<thead>
<tr>
<th>MEMBER</th>
<th>FLOOR BEAM No.</th>
<th>TEST*</th>
<th>t (mm)</th>
<th>L (mm)</th>
<th>REDUN.</th>
<th>INITIAL DATA</th>
<th>SMOOTHED DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b_e (mM)</td>
<td>b_e/t</td>
</tr>
<tr>
<td>COLUMN</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>TOP</td>
<td>42 J to P</td>
<td>16</td>
<td>6860</td>
<td>3</td>
<td>2278</td>
<td>142.375</td>
<td>.332</td>
</tr>
<tr>
<td></td>
<td>42 P to P</td>
<td>16</td>
<td>6860</td>
<td>3</td>
<td>2014</td>
<td>125.875</td>
<td>.294</td>
</tr>
<tr>
<td></td>
<td>42 C</td>
<td>16</td>
<td>6860</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>10</td>
<td>6860</td>
<td>3</td>
<td>2242</td>
<td>224.2</td>
<td>.327</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>10</td>
<td>6860</td>
<td>3</td>
<td>1586</td>
<td>158.6</td>
<td>.231</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>16</td>
<td>6860</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>10</td>
<td>6860</td>
<td>5</td>
<td>2116</td>
<td>211.6</td>
<td>.308</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>10</td>
<td>6860</td>
<td>5</td>
<td>1355</td>
<td>135.5</td>
<td>.227</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>10</td>
<td>6860</td>
<td>5</td>
<td>2054</td>
<td>205.4</td>
<td>.299</td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>12</td>
<td>7280</td>
<td>3</td>
<td>1251</td>
<td>104.25</td>
<td>.172</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>12</td>
<td>7280</td>
<td>3</td>
<td>1173</td>
<td>97.75</td>
<td>.161</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>12</td>
<td>7280</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>12</td>
<td>6310</td>
<td>3</td>
<td>1647</td>
<td>137.25</td>
<td>.261</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>12</td>
<td>6310</td>
<td>3</td>
<td>1350</td>
<td>112.5</td>
<td>.213</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>12</td>
<td>6310</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>12</td>
<td>6310</td>
<td>5</td>
<td>1517</td>
<td>126.42</td>
<td>.240</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>12</td>
<td>6310</td>
<td>5</td>
<td>1265</td>
<td>105.42</td>
<td>.200</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>12</td>
<td>6310</td>
<td>5</td>
<td>2705</td>
<td>225.42</td>
<td>.429</td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>12</td>
<td>6310</td>
<td>6</td>
<td>2645</td>
<td>217.92</td>
<td>.414</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>12</td>
<td>6310</td>
<td>6</td>
<td>2645</td>
<td>217.92</td>
<td>.414</td>
</tr>
<tr>
<td>Bottom</td>
<td>42 J to P</td>
<td>20</td>
<td>6860</td>
<td>3</td>
<td>1426</td>
<td>71.3</td>
<td>.208</td>
</tr>
<tr>
<td></td>
<td>42 P to P</td>
<td>20</td>
<td>6860</td>
<td>3</td>
<td>1271</td>
<td>63.55</td>
<td>.185</td>
</tr>
<tr>
<td></td>
<td>42 C</td>
<td>20</td>
<td>6860</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>18</td>
<td>6860</td>
<td>3</td>
<td>986</td>
<td>54.78</td>
<td>.144</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>18</td>
<td>6860</td>
<td>3</td>
<td>1332</td>
<td>74.00</td>
<td>.194</td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>18</td>
<td>6860</td>
<td>5</td>
<td>1200</td>
<td>66.67</td>
<td>.175</td>
</tr>
<tr>
<td></td>
<td>27 P to P</td>
<td>18</td>
<td>6860</td>
<td>5</td>
<td>1428</td>
<td>79.33</td>
<td>.208</td>
</tr>
<tr>
<td></td>
<td>27 C</td>
<td>18</td>
<td>6860</td>
<td>5</td>
<td>866</td>
<td>47.00</td>
<td>.123</td>
</tr>
<tr>
<td></td>
<td>27 J to P</td>
<td>18</td>
<td>6860</td>
<td>6</td>
<td>817</td>
<td>45.39</td>
<td>.119</td>
</tr>
</tbody>
</table>

Table 1: Effective Widths Computed from Transverse Strains

*J to P - Jetties to Pontoon
P to P - Pontoon to Pier Rings
C - Center Span Lift
Figure 1: Construction Sequence
Figure 2: Locations of Instrumented Cross Sections in the Rio Side Span
Figure 3: Transverse Strains at FB27 (Jetties to Pontoon)
Figure 4: Transverse Strains at FB42 (Jetties to Pontoon)
Figure 5: Transverse Strains at FB27 (Pontoon to Pier Rings)

Scale: 0 - 300 600 x 10^-6 cm/cm
Figure 6: Transverse Strains at FB42 (Pontoon to Pier Rings)
Figure 7: Transverse Strains at FB27 (Center Span Lift)
Figure 8: Transverse Strains at FB42 (Center Span Lift)
Figure 9: Flow Chart of Computer Program for the Determination of Effective Widths
a) Idealization of Actual Structure

b) Primary Structure

Figure 10: Model of Typical Transverse Frame for Analysis
Figure 11: Cantilever Idealization of Structure for Force Method
Figure 12: Moment (M), Shear (S), and Thrust (P) Diagrams for Unit Redundants
Figure 13: Secondary Stress Effects
Force to Restrained Flange Plate

Force on Unrestrained Member

Forces Caused by Redundants

Figure 14: Forces Acting on a Cross Section
Figure 15: Revised Model of Typical Transverse Frame for Analysis

a) Idealization of Actual Structure

b) Primary Structure
REFERENCES


A.1 Dimensions of Instrumented Sections

All of the electrical gage readings were taken on the 200-meter Rio side span of the three-span continuous girder. The six-lane double box section is 25.9 meters wide and has a depth varying from 5.69 meters at FB17 to 13.04 meters at FB57. The two boxes each have a width of 6.86 meters and are 6.34 meters apart.

A.2 Sequence of Readings

There were three stages in static studies in which electrical gages were used to measure strain and temperature changes. The first stage, the study under construction loads, is comprised of readings from three sets:

1) Readings taken on the north box of the Rio side span when it was transferred from two jetties, near the assembly site, to the pontoon (Readings Nos. 3.0 to 3.2 in Table A-1).

2) Readings taken on the north box of the Rio side span when it was transferred from the pontoon to the pier rings (Reading Nos. 3.3 and 3.4 in Table A-1).
3) Readings taken on both boxes of the Rio side span during the center span lift (Reading Nos. 4.0 to 4.2 in Table A-1).

The second stage represents the static readings taken on the completed structure during each of the four load positions (Fig. A-1) of twenty-one, 17.5-ton trucks (Reading Nos. 5.0 to 5.5 in Table A-1). Temperature studies, intended to investigate stresses created from changes in temperature, comprised the final third stage of readings (Reading Nos. 5.6 to 7.1 in Table A-1).

A.3 Placement of Gages

All readings were taken on the Rio side span at five cross section located at and between the supports. Figure A-2 shows that these cross sections were at floor beam 17 (FB17), floor beam 27 (FB27), floor beam 42 (FB42), floor beam 51 (FB51), and floor beam 57 (FB57).

Each cross section (identified by its floor beam) was chosen for some specific reasons:

FB17: This cross section located at an end support is subjected to statically determinate moment which can be easily calculated. This was particularly important for Position 3 of the test loads on the completed structure (See Fig. A-1).

FB27: This cross section was chosen because it has typical cross bracing. Also, it provided an
opportunity to study temperature distribution on an average-depth cross section within the span and thus subjected to wind effects.

FB42: Located near mid-span, this cross section experiences the greatest moment change while having small shear. This section, being without cross bracing, was selected because of its sensitivity to cross-sectional deformation and because of its usefulness in studying load distribution between the two box girders.

FB51: This cross section is located at the beginning of the haunch where non-linear normal stress distribution was expected. This section is also one of the deeper ones of the span.

FB57: This cross section is the deepest (13.04m) and is also located at an interior support. The haunch is the steepest and its effect on the stresses should be most pronounced. The large mass of the section and the reduced wind effect due to the piers under it provide a counterpart condition to FB27 for temperature studies.

With St. Venant's principle in mind, it was decided not to place the gages right at the floor beams and transverse stiffeners. Instead the gages were placed approximately twice the
longitudinal stiffener spacing from the floor beams to avoid local disturbances. The decision to locate the gages on a specific side of the floor beams was based on the following reasons (Fig. A-2):

FB17: The gages were placed on the Rio side to take advantage of the static determinacy of the cantilever for both moment and shear.

FB27: The Niteroi side was chosen because of a splice on the other side that might have caused local disturbances. Also, a special internal bracket was temporarily placed on the Rio side to avoid load overstressing when the girders were transported on the pontoons.

FB42: Since a scaffold had to be built to monitor dynamic stresses at a splice on the Rio side, it was decided to take advantage of the scaffold and place the gages there.

FB51: Not only temporary erection brackets but also a reinforcement truss caused local disturbance on the Rio side, thus the Niteroi side was chosen.

FB57: The Rio side was selected so that the data could be correlated with the analysis of other sections under study in the span.
A.4 Types of Gages

In the static study three types of electrical gages were used: linear, three-strain-gage rosettes, and temperature. While the linear and temperature gages have one-resistor components, the rosette consists of three one-resistor components oriented at 45 degrees to each other. The linear and rosette gages measure a change in strain by the change in resistance in the wire of the gage components created by a change in strain. Similarly, changes in temperature are registered by changes in resistance induced by changes in temperature in the wire of the gage. To ensure that changes in temperature in the long cables leading to the gages did not affect the readings, three wires were connected to each gage instead of two.

A.5 Gage Locations and Identification

Figures A-3 through A-8 locate and identify the electrical gages used. The linear gages running parallel to the roadway (longitudinal gages) are indicated by dots (●); those running perpendicular to the roadway (transverse gages) are indicated by dashes (¬). Temperature gages (located only at FB27 and FB57) are indicated by triangles (▲). Rosettes, indicated by crosses (+), are located at the position where the cross intersects the outline of the cross section.
The system for identifying and labeling gages was based on the fact that each cable from the data acquisition unit had six leads and each gage required three leads. Thus each cable was given a number (shown inside an ellipse in Figs. A-3 to A-8) and the two three-lead parts of each cable were designated by A and B; part A having black, yellow, and red leads and part B having blue, green and white leads. The arrowed lines going from one gage to another (Figs. A-3 to A-8) through one or more ellipses became the method of identifying gages. If it is not indicated, it is understood that A precedes B for each cable number. If the arrows go from a one-component gage to another one-component gage, then only one cable is used; the first gage (indicated by the arrows) is the A part and the second is the B part. Since rosettes have three gage components, the following order is used: the longitudinal component (parallel to the roadway) first, the diagonal component second, and the transverse component (perpendicular to the roadway) third. Thus, for example, in Fig. A-4 the arrows go from a single longitudinal gage through ellipses 43 and 44 to a rosette, two cables (Nos. 43 and 44) are needed (4 components). The A part of the first cable (No. 43) serves the longitudinal part of the rosette, and the A and B parts of the No. 44 cable serve the diagonal and transverse components of the rosette, respectively. This basic rule is used in all Figures A-3 to A-8 unless otherwise indicated in the ellipse.
A.6 Data Acquisition

Three different methods were used in the recording of strain readings. During the transfer of the north box girder from the jetties to the piers in October 1973 (Fig. A-2a), the readings were taken by hand. The Datran unit was housed temporarily in a wooden shack on the top flange of the girder. Since only 9/2 cables (19 gages of the 226 gages to be read) could lead into the switching box connected to Datran at once, two switching soldering stations were established (indicated by boxes and brushes in Fig. A-2), one in a wooden shack at FB27 and the other in the shack at FB51.

In December 1973, during the lifting of the center span, the more sophisticated B&F unit was used as the data acquisition device (Fig. A-2b). The B&F was stored in a shack on the deck and it recorded readings from both boxes automatically by means of a teletype. Since readings from the 357 gage components were being taken and the B&F could only handle 100, switching soldering stations were again needed; this time they were placed inside the box at FB27 and FB51 as shown symbolically in Fig. A-2 by panels and brushes.

Since the readings taken after December 1973 were on the completed structure, a truck was necessary to house the B&F unit (Fig. A-2c). By installing a set of plugs in the concrete curb at FB51, the truck housing the B&F unit could drive up and
be connected into the gaging system at any time. Switching at FB51 and FB27 inside the north box was necessary for these readings in the same manner as in December 1973.
<table>
<thead>
<tr>
<th>TRIP</th>
<th>READING NUMBER</th>
<th>DATE</th>
<th>START TIME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>17Jul73</td>
<td></td>
<td>No readings during this trip</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>03Sep73</td>
<td></td>
<td>No readings (Installation of Instrumentation)</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>08Oct73</td>
<td>16:10</td>
<td>Side span on jetties</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>09Oct73</td>
<td>13:00</td>
<td>Side span on jetties</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>10Oct73</td>
<td>00:20</td>
<td>Side span on pontoon</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>11Oct73</td>
<td>22:25</td>
<td>Side span on pontoon</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>12Oct73</td>
<td>05:50</td>
<td>Side span on pier rings</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
<td>12Dec73</td>
<td>00:36</td>
<td>Pontoon in water</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>13Dec73</td>
<td>09:30</td>
<td>Pontoon suspended (day)</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>13Dec73</td>
<td>20:40</td>
<td>Pontoon suspended (night)</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
<td>25Feb74</td>
<td>06:45</td>
<td>Zero readings - test loads</td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td>24Feb74</td>
<td>22:52</td>
<td>Load position 1</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>25Feb74</td>
<td>03:25</td>
<td>Load position 2</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>25Feb74</td>
<td>20:36</td>
<td>Zero reading - test loads</td>
</tr>
<tr>
<td></td>
<td>5.4</td>
<td>25Feb74</td>
<td>23:58</td>
<td>Load position 3</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>26Feb74</td>
<td>02:35</td>
<td>Load position 4</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>26Feb74</td>
<td>14:15</td>
<td>Temperature study</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>27Feb74</td>
<td>11:05</td>
<td>Temperature study</td>
</tr>
<tr>
<td>6</td>
<td>6.1</td>
<td>10Jun74</td>
<td>08:56</td>
<td>Temperature study</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>11Jun74</td>
<td>07:50</td>
<td>Temperature study</td>
</tr>
<tr>
<td>7</td>
<td>7.1</td>
<td>16Jan75</td>
<td>23:00</td>
<td>Temperature study</td>
</tr>
</tbody>
</table>

Table A-1: Sequence of Electrical Gauge Static Readings
Load Position 3

Load Position 4

*All dimensions are in meters

Figure A-1: Position of Test Loads in February 1974
(Convoy of 21 17.5 Ton Trucks)
a. Jetties - Piers

b. Center Span Lift

c. Completed Bridge

Figure A-2: Systems of Data Acquisition of the Rio Side Span
Figure A-3: Location of Gages at FB17

Gage Legend:
- Longitudinal
- Transverse
+ Rosette
△ Temperature
Figure A-4: Location of Longitudinal, Rosette, and Temperature Gages at FB27

Gage Legend: • Longitudinal  - Transverse  + Rosette  ▲ Temperature
Figure A-5: Location of Transverse Gages at FB27

Gage Legend:  • Longitudinal
               - Transverse
               † Rosette
               ▲ Temperature
Figure A-6: Location of Gages at FB42

Gage Legend:
- Longitudinal
- Transverse
+ Rosette
▲ Temperature
Figure A-7: Locations of Gages at FB51

Gage Legend:
- Longitudinal
- Transverse
+ Rosette
△ Temperature
Legend: See Fig. A-3

Figure A-8: Locations of Gages at FB57
APPENDIX B: DATA PREPARATION

B.1 Data Preparation

The electrical gage readings of Table A-1 were acquired by two different means. The Datran readings of October 1973 were recorded by hand and the B&F readings from December 1973 to January 1975 by teletype on paper tape. Both forms of recorded data had to be transferred to computer cards in a suitable format before the information could be reduced by the computer. As shown in the table, the data was assigned reading identification numbers in accordance with the trips to Río de Janeiro by the Lehigh team.

B.2 Analysis of Stresses Due to Construction and Test Loads

Once the cards were sorted and categorized they were ready to be reduced by the computer. For the construction and test loads (Rdgs. 3.0 to 5.5) a special program was used. The inputs for this program are the zero and accompanying reading for each set, the temperature calibrations for each reading, and the gage identification information. This program yielded changes in strain, pseudo changes in stresses,* temperature, changes in tem-

*Pseudo stress change is Young's modulus times the change in strain which is not necessarily the actual change in stress.
perature, and an analysis of rosette readings. From the changes in strains from the three rosette components the program calculated $\sigma_x$, $\sigma_y$, $\tau_{xy}$, $\sigma_1$, $\sigma_2$, $\tau_{max}$, and the principal directions. The final step of this portion of the static studies was to plot $\sigma_x$, $\tau_{xy}$ and the transverse strains so that any trends in the readings and the consistency of the readings could be observed. Figures 3 to 8 represent such plots pertinent to the Poisson's effect study of this thesis.

B.3 Analysis of Stress Due to Change in Temperature

The analysis of stresses due to changes in temperature (temperature studies) was performed on data taken in February 1974, June 1974, and January 1975 (Table A-1, Reading Nos. 5.6 to 7.1). The temperature study in February 1974 was conducted to establish a general distribution of temperature over the cross section of the bridge. Because this study consisted only of two sets of readings, the data was not time dependent and thus was reduced using the program described in Section B.2.

The data of June 1974 and January 1975 were time dependent, consisting of many sets of static readings taken at certain intervals over a period of time. Another program was written so that this new parameter (time) could be taken into account. This program calculated the temperatures and strains and stored them...
in matrices. From these matrices the data could be curve-fitted or plotted.

This program was used on the data from June 1974. However, due to the limited scope of this data, only the general pattern of the temperature change could be obtained.

In January 1975, the readings were complete in number, but rather erratic and consequently matrix storage and curve-fitting were impractical. Because of this the program was modified and the results were only plotted and the smoothening and curve-fitting was done by hand.
APPENDIX C: FUNDAMENTAL MATRICES FOR FORCE METHOD ANALYSIS

C.1 Review of Equations

As described in Section 3.5, the basic equation of the member bar forces is:

\[ S = (B_0)R + (B_1)X \]  

(1)

But since \( R = 0 \):

\[ S = (B_1)X \]  

(2)

where:

\[ X = -((B_1)^T \cdot F \cdot B_1)^{-1} \cdot (B_1)^T \cdot V \]  

(3)

In order to solve these equations, the \( B_1 \), \( F \), and \( V \) matrices must be formulated. The \( B_1 \) and \( F \) matrices are formulated routinely and are listed in Figs. B-1 and B-2, respectively. All notation is defined in Chapter 3 and dimensions are shown in Fig. 10.

The remaining \( V \) matrix is formulated below.

C.2 Formulation of \( V \) Matrix

By definition, the \( V \) matrix is a list of the deflections at the end of the released cantilever elements resulting from the applied loads (in this case, Poisson's effect). These deflections are the rotation (\( \theta \)), the transverse displacement (\( \nu \)), and the elongation (\( e \)). The only effects on the released elements (primary structure) are the curvatures, \( \phi \), and axial strains, \( \varepsilon \), described in Section 3.5. Since shear deformations are negligible,
the deflections can be calculated from the following equations:

\[ \Theta = \int_0^L \phi \, dx \]  \hspace{1cm} (C-1) \\
\[ \nu = \int_0^L \phi \, x \, dx \]  \hspace{1cm} (C-2) \\
\[ \varepsilon = \int_0^L \varepsilon \, dx \]  \hspace{1cm} (C-3) \\

As in Section 3.5 \( L \) is the length of the member along the \( x \)-axis with the origin at the released end of the member (the cantilevers of Fig. 11).

The \( V \) matrix then takes the form of a column matrix:

\[ V = \{ \theta_1 \nu_1 \sigma_1 \theta_2 \nu_2 \sigma_2 \theta_3 \nu_3 \sigma_3 \theta_4 \nu_4 \sigma_4 \theta_5 \nu_5 \sigma_5 \} \]  \hspace{1cm} (C-4)

where the subscripts are the member numbers. The final form of the \( V \) matrix is given in Fig. C-3 after making the needed calculations. The notation of the \( V \) matrix is defined in Section 3.5 and the dimensions \( D, W, \) and \( H \) are shown in Fig. 10.

With all the needed matrices formulated, the redundants \( X \) can be solved with Eq. 3 and the strains and stresses computed as described in Sections 3.6 and 3.7.
\[
\begin{bmatrix}
1 & -W & 0 & 0 & 0 \\
0 & 0 & +1 & 1 & +\cos(\tan^{-1} \frac{D}{W}) \\
0 & -1 & 0 & 0 & -\sin(\tan^{-1} \frac{D}{W}) \\
1 & 0 & 0 & 0 & 0 \\
0 & +1 & 0 & 0 & 0 \\
0 & 0 & +1 & 0 & 0 \\
1 & 0 & -D & 0 & 0 \\
0 & 0 & -1 & 0 & 0 \\
0 & +1 & 0 & 0 & 0 \\
1 & -W & -D & 0 & -W\sin(\tan^{-1} \frac{D}{W}) \\
0 & -1 & 0 & 0 & -\sin(\tan^{-1} \frac{D}{W}) \\
0 & 0 & -1 & 0 & -\cos(\tan^{-1} \frac{D}{W}) \\
0 & 0 & 0 & -D & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & +1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

Figure C-1: Matrix $B_1$, Bar Forces Due to Unit Redundant Forces Applied on the Primary Structure
\[
\begin{bmatrix}
\frac{D}{E(I_v)} & -\frac{D^2}{2E(I_v)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{D^2}{2E(I_v)} & \frac{D^3}{3E(I_v)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{D}{E(A_y)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{W}{E(I_b)} -\frac{w^2}{2E(I_b)} & \frac{D}{2E(I_v)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{w^2}{2E(I_b)} \frac{W^3}{3E(I_b)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{W}{E(A_y)} -\frac{w^2}{2E(I_v)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{D}{E(I_c)} -\frac{w^2}{2E(I_c)} & \frac{H^2}{2E(I_c)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{w^2}{2E(I_c)} \frac{W^3}{3E(I_c)} & \frac{H^3}{3E(I_c)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{H}{E(A_y)} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{\frac{D^2+w^2}{E(A_y)}} & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

*\(A_d\) = Area of Member 5

Figure C-2: Matrix F, Total Structure Flexibility Matrix
Figure C-3: Matrix V, Deflections at the Ends of the Released Members from Poisson's Effect
VITA

John E. O'Brien, son of William and Helen O'Brien, was born November 14, 1951 in Baltimore, Maryland. In June of 1969 the author graduated from Mt. Pleasant High School in Wilmington, Delaware. Four years later, in June of 1973, he received his Bachelor of Science Degree from the University of Delaware. Since August 1973, the author has been attending Lehigh University taking courses toward a Master's Degree and working part-time as a Research Assistant.