DYNAMIC TESTS OF MODEL STEEL STRUCTURES

by
Wayne L. Stewart, Pierce E. Rowe
and Peter Jan Pahl

Supervised by
Robert J. Hansen
and
Peter Jan Pahl

November, 1965

Contract No. NBy-32267

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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November, 1965

School of Engineering
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts
The objective of this research project is the development of modelling techniques for steel structures and an investigation of the effect of strain rate on the resistance function of structural elements. The work proceeded in four phases: a dynamic loading machine was developed, dynamic material properties were determined in a series of tensile tests, 16 static and dynamic tests were performed on simply supported beams loaded at the third points, and a series of 16 static and dynamic tests was performed on fixed ended portal frames subjected to a lateral load at the level of the girder.

The dynamic loading machine is capable of rise times of 3 milliseconds or more and maximum loads of 2000 pounds. It can also be used as a static loading machine.

The beam tests indicate that the resistance function in bending for SAE 1113 steel models of 8 WF 67 sections is essentially independent of the strain rate. An equivalent single degree of freedom system yields good predictions of the experimental deflection-time curves for the beams. The consistency of tests on essentially identical beams is good. Tests on SAE 1020 steel models of 14 WF 103 beams indicate that for this steel, the resistance function in bending is strain rate dependent.

The frame tests confirm the observations made during the beam tests. The resistance function of frames manufactured from SAE 1113 steel is essentially independent of the strain rate, and the theoretically predicted and experimentally observed static load-deflection curves are in good agreement if the flexibility of the base and the knee connection are accounted for. The average relative fixity of the frames at their base is in excess of 90%. Repeated tests on essentially identical frames are consistent, and a dynamic analysis based on an equivalent single degree of freedom system yields good predictions of the experimental deflection-time curves.
Generally, it is concluded that model studies of steel structures provide an excellent experimental tool. Very sensitive tests for the investigation of strain rate effects have been developed. The necessary apparatus and techniques have been refined and initial difficulties eliminated so that a large number of additional tests on models with a variety of geometric configurations and material properties could be performed rapidly and reliably. These tests might significantly extend our understanding of the dynamic behavior of steel structures.
ACKNOWLEDGEMENT

This research has been conducted by the Department of Civil Engineering of the Massachusetts Institute of Technology for the United States Civil Engineering Laboratory. The project has been supervised by Dr. Robert J. Hansen and Dr. Peter Jan Pahl. The construction and erection of the loading machine was supervised by Dr. Gerald M. Sturman. Mr. Wayne L. Stewart and Mr. Pierce E. Rowe have been research assistants on the project. They have performed the experimental studies and have participated in the writing of this report.

The authors would like to thank Mr. Donald Gunn of the Structural Models Laboratory for his aid in the development of the loading machine and the beam and frame test stands. The report has been typed by Miss Jane Smith, whose neat work is particularly appreciated.
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<tr>
<td>a</td>
<td>acceleration</td>
</tr>
<tr>
<td>(A_{j})</td>
<td>acceleration at time (t_j)</td>
</tr>
<tr>
<td>(A_f)</td>
<td>area of one flange</td>
</tr>
<tr>
<td>(A_s)</td>
<td>area of stiffener</td>
</tr>
<tr>
<td>(A_w)</td>
<td>area of web</td>
</tr>
<tr>
<td>d</td>
<td>depth of section</td>
</tr>
<tr>
<td>E</td>
<td>modulus of elasticity</td>
</tr>
<tr>
<td>(f_x)</td>
<td>scale ratio for the variable (x)</td>
</tr>
<tr>
<td>(f_y)</td>
<td>dynamic yield stress</td>
</tr>
<tr>
<td>(f_{yo})</td>
<td>static yield stress</td>
</tr>
<tr>
<td>(F_{avg})</td>
<td>average force in flanges</td>
</tr>
<tr>
<td>(g)</td>
<td>specific mass</td>
</tr>
<tr>
<td>(g(\dot{\varepsilon}))</td>
<td>a function of the strain rate</td>
</tr>
<tr>
<td>h</td>
<td>height of frame</td>
</tr>
<tr>
<td>H</td>
<td>length of finite difference element</td>
</tr>
<tr>
<td>I</td>
<td>% increase in yield stress due to strain rate effect</td>
</tr>
<tr>
<td>(I_1)</td>
<td>moment of inertia of frame column</td>
</tr>
<tr>
<td>(I_2)</td>
<td>moment of inertia of frame girder</td>
</tr>
<tr>
<td>k</td>
<td>stiffness ratio, see appendix C.1</td>
</tr>
<tr>
<td>K</td>
<td>number of finite elements in beam</td>
</tr>
<tr>
<td>L</td>
<td>length</td>
</tr>
<tr>
<td>m</td>
<td>mass per unit length of beam</td>
</tr>
<tr>
<td>(m_1)</td>
<td>mass of frame column</td>
</tr>
<tr>
<td>(m_2)</td>
<td>mass of frame girder</td>
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<tr>
<td>M</td>
<td>moment</td>
</tr>
<tr>
<td>(M_b)</td>
<td>mass of beam</td>
</tr>
<tr>
<td>(M_c)</td>
<td>mass of load cell</td>
</tr>
<tr>
<td>(M_e)</td>
<td>mass of equivalent system</td>
</tr>
<tr>
<td>(M_p)</td>
<td>plastic moment capacity</td>
</tr>
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<td>P</td>
<td>applied force</td>
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R  resistance  
S  shear force  
t  time  
T  natural period  
\( \dot{Y}_c \)  corrected frame deflection, see appendix C.  
\( Y_f \)  total frame deflection  
\( Y_k \)  deflection due to frame knee flexibility  
\( Y_1 \)  frame deflection when first hinge forms  
\( Y_2 \)  frame deflection when second hinge forms  
\( \varepsilon \)  strain  
\( \sigma \)  stress  
\( \theta \)  rotation of frame knee
Chapter 1

INTRODUCTION

1.1 Objectives

The major objective of this investigation is to study the effect of strain rate on the resistance function of simply supported beams and fixed based portal frames experimentally and to compare the observations to suitable mathematical theories. A second objective is the development of a dynamic loading system which will provide a means of varying the strain rate within the range of interest. The general characteristics required of the loading system are outlined in Section 2.1.

The behavior of the fixed ended portal frames is compared to that observed in full scale tests performed at the U. S. Naval Civil Engineering Laboratory, Port Hueneme, California.

1.2 Laws of Similitude for Dynamic Studies

In dynamic studies, the response of structures is influenced by both the inertia force due to the mass of the structure and the effect of strain rate which changes the material properties. It is readily shown by the theory of dimensions(1) that the law of similitude for body forces requires that

\[ \frac{f_E}{g_{y_0}} = \frac{a}{L} \]

where

\[ f_E = \text{scale ratio for the modulus of elasticity} \]
\[ f_g = \text{scale ratio for the specific masses} \]
\[ f_a = \text{scale ratio for the accelerations} \]
\[ f_L = \text{scale ratio for the lengths} \]

To investigate similitude for strain rate effects, set

\[ \sigma_y = \sigma_{y_0} g(\dot{\varepsilon}) \]
where \( \sigma_y \) = dynamic yield stress
\( \sigma_{yo} \) = static yield stress
\( g(\dot{E}) \) = a function of the strain rate

Since the modulus of elasticity \( E \) is the same in model and prototype, it follows that the scale ratio \( f_\sigma \) for stresses is given by

\[ f_\sigma = f_E = 1 \]  \hspace{1cm} (1.3)

Equation (1.2) becomes

\[ g_m(\dot{\varepsilon}_m) = g_p(\dot{\varepsilon}_p) \]  \hspace{1cm} (1.4)

where \( m \) refers to the model and \( p \) to the prototype. If similar steels are used in the model and in the prototype, the function \( g \) is the same for both. Condition (1.4) can then only be satisfied if

\[ \dot{\varepsilon}_m = \dot{\varepsilon}_p \]

so that

\[ f_\varepsilon = 1 \]  \hspace{1cm} (1.5)

The implications of condition (1.5) are as follows: the scale ratio \( f_t \) for time \( t \) is given by

\[ f_t = f_{-1}^{\varepsilon} = 1 \]

The scale ratio \( f_a \) for accelerations \( a \) is

\[ f_a = f_L f_t^{-2} \]  \hspace{1cm} (1.6)

Since the length scale ratio \( f_L = 0.1 \), this yields

\[ f_a = 0.1 \]  \hspace{1cm} (1.7)
The scale ratio $f_g$ for specific masses is unity, and substitution of result (1.7) into the law of similitude (1.1) with $f_L = 0.1$ leads to

$$f_E = 0.01$$  \hspace{1cm} (1.8)

This result contradicts condition (1.3). The laws of similitude (1.1) for mass effects and (1.5) for strain rate effects cannot be satisfied simultaneously. Because this study is primarily concerned with strain rate effects, rise times will be chosen so as to model strain rate rather than inertia force effects.

Suppose it were chosen to satisfy the law of similitude (1.1) for inertia force effects. Since the model and prototype steels have the same moduli of elasticity and the same specific masses,

$$f_E = f_g = 1$$

The length scale ratio has already been chosen as

$$f_L = 0.1$$

Substitution into equation (1.1) leads to

$$f_a = 10$$

It now follows from equation (1.6) that

$$f_t = 0.1$$

For strain rate effects the value of $f_t$ was unity. The strain rate in the model would be ten times that in the prototype if condition (1.1) is satisfied. The increase in material strength due to the strain rate would be larger in the model than in the prototype, which contradicts condition (1.3).
In view of these considerations, no attempt is made to model a particular prototype. Instead, for both the beams and the frames, theories are developed, applied to the actual model structures tested, and verified by comparison to the experimental results. The mathematical theories can then be employed to predict prototype behavior since the theories unlike the model can account for the actual strain rate effects in the prototype.

1.3 Selection of Rates of Loading

The model tests are concerned with strain rate effects. A survey of previous studies \((2.5)\) indicates that a significant increase in the yield stress of steel can be expected for a strain rate of \(0.1 \text{ sec}^{-1}\). Steel has a yield strain of approximately 0.001. This implies that the yield strain should be reached within a period of the order of \(0.01\) second if significant changes in the resistance function are to be obtained. Therefore, the desired rise time of the loading machine is 10 milliseconds or less. In order to permit a study of the effects of strain rate, the machine should be capable of producing variable rise times ranging from this minimum of less than 10 to a maximum of more than 100 milliseconds.

1.4 Contents of the Report

The development and the characteristics of the loading device are described in Chapter 2. The determination of the material properties is summarized in Chapter 3. A series of static and dynamic tests on 14 simply supported beams is described and evaluated in Chapter 4. Chapter 5 contains a discussion of a series of 16 static and dynamic tests on fixed ended portal frames. Mathematical theories for dynamically loaded simply supported beams and fixed ended portal frames, accounting for the effect of strain rate on the material properties, are described in Appendices A, B, and C. Additional beam tests, using models manufactured from a different steel, are presented in Appendix D.
Chapter 2

THE LOADING MACHINE

2.1 Selection of a Loading System

The selection of a suitable loading system is primarily dependent upon the rise time that is to be achieved. It has been discussed in Chapter 1 that for the study of strain rate effects with which this project is concerned, rise times ranging from less than 5 to more than 100 milliseconds are desired. The selected system should be capable of maximum loads of the order of 2000 pounds. The load function should be reproducible, and as independent as possible of the characteristics of the test specimen. Since the specimens will be deformed into the plastic range, significant motion of the point of load application, with a maximum of approximately 3 inches, is to be expected. Finally, the configuration and mechanics of the loading system should be simple to reduce cost, to speed the construction and development and to ease maintenance.

A differential pressure machine, consisting essentially of a piston moving in a cylinder, is considered to be the simplest type of dynamic loading system. Pressure is applied suddenly to one side of the piston, and the load is transmitted through the piston rod to the specimen. The magnitude of the load is controlled by varying the pressure intensity. Gas pressure is preferred to hydraulic pressure because it can be supplied by a simple and tidy system.

A sudden pressure differential can be achieved in this device by one of two methods: in the first, gas at high pressure is suddenly introduced through a rapidly opening valve into the cylinder on one side of the piston; in the second, equal forces are gradually built up on both sides of the piston, then the pressure on one side is suddenly released. While the injection of gas through very rapidly opening valves theoretically leads to shorter rise times (3), the commercially available solenoid valves are too slow for the desired rise times and working pressures.
Within the scope of this project, the development of faster valves did not seem to be an attractive solution.

The gas ejection method was therefore preferred. While the equal force on both sides of the piston is being built up, the exhaust port is covered by a thin plastic diaphragm. The gas supply is sealed by means of valves, then the diaphragm is punctured suddenly by a rapidly moving cutter. The gas on one side of the piston escapes and the unbalanced pressure is taken up by the piston rod. The rise time is varied by means of orifice inserts which decrease the area of the exhaust port so that the gas escapes less rapidly. From past experience at M.I.T. with devices of a similar kind, it was felt that the proposed loading device could be developed within a relatively short period at a moderate cost, and that it would meet the requirements stated above.

2.2 Development of the Dynamic Loading Machine

In this section, the initial design of the loading device, and a series of tests leading to significant modifications, will be described. A period of nine months, starting at the initiation of the project, was needed to develop the loading machine sufficiently to obtain the short rise time required for the beam and frame tests described in Chapters 4 and 5. The final version of the loading machine is shown diagramatically in Figure 2.1.

2.2.1 Initial Configuration - A hydraulic cylinder with a 4 inch diameter cylinder bore and a 4 inch stroke was selected. The upper end of the piston rod was removed so that the rod was flush with the top face of the piston. Circular neoprene pads, 1/8" thick, were epoxied to each face of the piston to prevent it from damaging the ends of the cylinder. Three 1/2" diameter ports were drilled in both the upper and lower ends of the cylinder. In one of these ports at each end, a diaphragm holder was inserted. Small solenoids (6 lb. maximum pull) were used to propel a 1/8" diameter pointed rod, attached to the solenoid plug, into a thin diaphragm, causing it to rupture. A time delay circuit activated the upper solenoid at some specified time after the acti-
FIGURE 2.1
FINAL CONFIGURATION OF DYNAMIC LOADING MACHINE
vation of the lower solenoid (see section 2.3). This made it possible to cut off the load function at a desired moment.

At the lower end, the two remaining ports were plugged while at the upper end, a reservoir tank was attached at each port. The reservoir tanks were 2.5 lb CO₂ fire extinguisher tanks without valves. These tanks increase the total volume of gas behind the piston, so that, when the piston rod moves forward, the increase in the volume of the gas due to the displacement of the piston is small compared to the total volume. Consequently, the magnitude of the applied load is not influenced significantly by the flexibility of the specimen. The initially existing port at each end of the cylinder was connected by means of a rubber hose through pressure regulating gages to a tank of bottled nitrogen. The tanks and gages can be placed at a convenient distance from the testing area. A load cell as described in section 2.3 was screwed onto the piston rod to permit measurement of the load applied to the specimen.

The machine was attached to a 8' by 6' loading frame, consisting of 12 WF 27 steel beams mounted on concrete pedestals, as shown in Figure 4.5.

2.2.2 Subsequent Modifications - Tests of the loading machine in its initial configuration indicated that the rise time was too large when compared to the strain rates desired in the experiments. The rise times achieved at this stage were of the order of 25 milliseconds.

The two additional exhaust ports at the lower end of the cylinder were then unplugged and fitted with diaphragms and solenoid systems, since the larger exhaust area was expected to lead to a decrease in the rise time. This modification was not successful. While the rise time was decreased, the bursting patterns of the diaphragms were inconsistent. Generally, only one diaphragm ruptured completely while the other two exhaust ports were only partially opened. Thus most of the gas still escaped through only one exhaust port. The reproducibility of the load function was poor. The two extra ports were once again plugged.

In the original system, the diaphragm was punctured by a pin, creating a small hole in the diaphragm. The escaping gas then forced
the diaphragm to rupture along several lines, radiating outward from the pin hole, thereby opening the port completely. By replacing the pin with a cylindrical blade, which cuts the diaphragm completely around its outer edge, the gas can be allowed to escape more freely. A much larger force is, however, required to cut the diaphragm completely than is necessary to puncture a small hole. Several cutters and guidance systems were designed and a much larger solenoid (50 lb. max. pull) installed before the diaphragm could be cut cleanly. The elements of the cutting and guidance system are shown in Figures 2.2 and 2.3. A detail photo of the assembled cutting system attached to the larger solenoid is shown in Figure 2.4. Note in the same figure that the initial pin system at the upper end of the cylinder has not been replaced.

The pressure source initially consisted of bottled nitrogen. This was replaced by helium. The velocity of a gas is directly proportional to its velocity of sound. The velocity of sound of helium is 2.78 times larger than that of nitrogen so that the rise time of the loading machine could be expected to decrease approximately by a factor of 3 when helium was used instead of nitrogen. Experimental observations are shown in Figure 2.5. The graph also indicates the effect of the diaphragm type on the rise time. The beam and frame tests were carried out with 0.005" thick lumarith diaphragms.

The final configuration of the machine is shown in Figures 2.1 and 2.10. The photo was taken while the machine characteristics were being determined.

2.3 Measuring and Recording Equipment

2.3.1 General Description - In order to summarize the general characteristics of the measuring system and the function of the individual components, a brief description of the testing procedure is given in this section. The following measuring devices were employed: a load cell which is attached to the piston rod of the loading machine and measures the load applied by the machine; a potentiometer which measures
FIGURE 2.2
CUTTING AND GUIDANCE SYSTEM
FIGURE 2.3
Photograph of Cutting Device

FIGURE 2.4
Photograph of Assembled Cutting System
FIGURE 2.5
EFFECT OF DIAPHRAGM AND GAS TYPE ON RISE TIME
the displacement of the model; and, in the case of the frame tests, another load cell which measures the horizontal reaction at a column base. The output from each transducer is a change of voltage which is recorded as a function of time by photographing the screen of a single sweep oscilloscope. The measuring system is powered by an ordinary 12 volt storage battery.

Several minutes before a test is conducted, the system is activated in order to allow the various components to warm up and stabilize. The loading piston is brought into position against the model and gas at the desired pressure is gradually introduced into both chambers of the cylinder. The lens shutters of the oscilloscope cameras are opened and immediately thereafter the machine is activated. The current flowing to the solenoid triggers the oscilloscope, where the change of voltage in the various transducers is recorded as a function of time by a light beam traversing the screen.

2.3.2 Power Supply - After tests with various other D. C. power supplies, a 12 volt storage battery was finally selected. It provides an inexpensive and reliable power supply with essentially no short-time voltage fluctuations. Other commercially available D. C. power supplies exhibit voltage fluctuations which, at the oscilloscope sensitivities used, cannot be tolerated. The voltage input to the measuring system is adjusted by means of two potentiometers connected as shown in Figure 2.6, and is measured by a Weston Model 301 voltmeter.

2.3.3 Load Cells - The load cell used to measure the force applied by the piston rod consists of a 1 inch diameter high strength aluminum tube (7075-T6) with four Baldwin-Lima-Hamilton electric resistance strain gages, type CBD-7, connected in a four arm bridge which cancels bending strains, as shown in Figure 2.7. The load cell is screwed onto the piston rod. Two different attachments can be screwed to the end of the load cell. One attachment provides a flat end and is intended for use against a surface which does not rotate. It is used in the beam tests. The second end attachment consists of a seated ball which bears against the model and permits rotation. This attachment is used to apply a lateral load in the frame tests, as described in Section 5.4.
FIGURE 2.6
WIRING DIAGRAM
CROSS SECTION OF LOAD CELL

END PIECE 1

END PIECE 2

GAGE LOCATIONS

FIGURE 2.7
7075-T6 ALUMINUM LOAD CELL
The load cell used to measure the horizontal reaction at the base of the frames is shown in Figure 5.4. It consists of a flat bar of mild steel connected to a fixed support at one end and the moveable column at the other end. The column moves laterally by a very small amount to strain the load cell. A four arm bridge of BLH-CBD-7 gages is attached to the steel bar, as shown in Figure 5.4.

Both load cells are powered by the storage battery described in section 2.3.2. The voltage change across the terminals of the cells is measured by means of oscilloscopes and is recorded on photographs. The circuitry is shown schematically in Figure 2.6. Both loads cells have a 6 volt power input and are used with oscilloscope sensitivity settings ranging between 0.5 and 2.0 mv/cm., depending upon the maximum load used in the particular test.

The load cell was calibrated against a proving ring, which had previously been calibrated against an Instron testing machine. The results of the calibration test are shown in Figure 2.8. The output of the proving ring is 100 microinch per inch for every 29.4 pounds of load. The output of the cell is 1 millivolt per 420 pounds of load. The safety of the load cell was verified by means of a compression test in the Instron machine, in which a maximum load of 5000 pounds was applied. The reaction measuring cell was calibrated directly in the Instron machine. It has an output of 1 millivolt per 71.4 pounds of load.

2.3.4 Deflection Measuring Instrument — The deflection sensor is a linear motion conductive plastic potentiometer, model number LMPS-230, manufactured by the New England Instrument Company, Natick, Massachusetts. This instrument has a resistance of 100K-ohms ± 10%, independent linearity of ± 1% and a stroke length of 3.25 inches. Movement of the potentiometer rod causes a change in resistance between the wiper and one end terminal. The voltage drop is recorded on an oscilloscope.

The calibration was performed by measuring the rod movement accurately with an Ames dial gage, recording the corresponding voltage
FIGURE 2.8
CALIBRATION CURVES FOR LOAD AND REACTION CELLS
change. During the static tests of both the beams and the frames, dial gages were used in addition to the potentiometer deflections. Thus a further calibration of the instrument in place was performed. A power input of 6 volts and an oscilloscope sensitivity of 0.5 volts/cm. were used for all tests. The output is 1 volt per 0.61 inches of movement of the rod.

2.3.5 Oscilloscopes - Two Tektronix, type 502, dual-beam oscilloscopes with mounted Polaroid cameras were used to record the changes in voltages across the terminals of the various transducers.

2.4 Machine Characteristics

Tests for the determination of the machine characteristics were carried out on an essentially non-deformable specimen as shown in Figure 2.10. The parameters varied during this testing were the piston setting, the gas pressure, and the area of the opening in the orifice insert.

2.4.1 Testing Procedure - The diaphragms were clamped in the positions indicated in Figure 2.1 and the cutter was attached to the solenoid. Then gas was introduced into the cylinder on both sides of the piston. Due to the presence of the piston rod, the lower face of the piston must be subjected to a higher pressure than the upper face if there is to be no force in the piston rod. Therefore, the pressure in the lower cylinder chamber was always kept approximately 5 psi higher than in the upper chamber. Just before the desired test pressure was reached, the pressure on the lower side was increased until the piston rod rose off the specimen. Then the pressure on the upper side was set at the desired test pressure. Finally, the pressure on the lower side was reduced until the piston rod once again rested on the specimen. The valves connecting the cylinder with the pressure sources were closed. Activation of the solenoid by means of a switch let the machine load the specimen. A typical photo of a load-time curve is shown in Figure 2.9. In this photograph, the horizontal scale is 5 milliseconds per cm. and the vertical scale is 420 pounds per cm. The side length of the squares in the photograph is 1 cm.
FIGURE 2.9
Oscilloscope Output

FIGURE 2.10
Test of Machine Characteristics
2.4.2 Test Results - The piston setting was varied from 1 to 3 inches so that piston movement from 1 to 3 inches would have been possible if flexible specimens had been tested. This covers the normal range of displacements that would probably be desired in testing a deformable specimen of the geometry and characteristics of our experiments. From the results, shown in Figure 2.12, it can be seen that for a piston setting of less than two inches, the rise time is almost directly proportional to the piston setting. At a 1 inch setting, the rise time varies from 3 to 5 milliseconds depending on the gas pressure. A test with a piston setting of approximately 1/4" at a pressure of 100 psi, which is not shown on the graph, yielded a rise time of 1 millisecond.

The gas pressure was varied from 50 to 150 psi as shown in Figure 2.13. The rise time is essentially independent of the pressure.

The area of the orifice insert ranged from 0.546 to 0.093 sq. in. Test results are shown in Figure 2.11. By using the smaller inserts, the rise times can be increased until the loading is essentially static.

Some preliminary tests on solid steel beams were performed to determine the machine characteristics when relatively flexible specimens are loaded. The tests indicated that in the range of practical interest, the machine characteristics are essentially independent of the flexibility of the loaded specimen. This was confirmed later in the beam and frame tests, as described in Chapters 4 and 5.

In addition to rise times from 1 to 1000 milliseconds which can be achieved by operating the device as a dynamic loading machine, static tests can be performed by adjusting the gas supply valves manually.
FIGURE 2.11
EFFECT OF ORIFICE AREA ON RISE TIME (PRESSURE 100 PSI)
FIGURE 2.12
EFFECT OF PISTON STROKE ON RISE TIME

FIGURE 2.13
EFFECT OF GAS PRESSURE ON RISE TIME
Chapter 3

MATERIAL PROPERTIES

3.1 Introduction

The 1 in 10 scale models of 8 WF 67 and 8 WF 31 sections used during the experiments were machined from solid square bars. In order to maintain the desired accuracy, a steel with good machinability was selected. The manufacturer, Special Shapes Co., Downers Grove, Illinois, suggested S.A.E. 1113 steel. The chemical composition of S.A.E. 1113 steel compares as follows with that of structural steel A 36:4:

<table>
<thead>
<tr>
<th></th>
<th>Carbon</th>
<th>Manganese</th>
<th>Phosphorus</th>
<th>Sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.A.E. 1113</td>
<td>0.13</td>
<td>0.8 - 1.2</td>
<td>0.04 - 0.09</td>
<td>0.25 - 0.35</td>
</tr>
<tr>
<td>A 36</td>
<td>0.28</td>
<td>0.8 - 1.1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Since the objective of this investigation was the study of strain rate effects, the dependence of the properties of this steel on the strain rate had to be determined. A series of tests conducted by means of an Instron machine at M.I.T. indicated that the increase of the dynamic yield stress over the static yield stress for the S.A.E. 1113 steel was somewhat less than for the conventional A 36 steel, but still considerable at the strain rates of 0.1 sec\(^{-1}\) expected in the beam and frame tests. Additional tensile tests at very high strain rates were performed by the U.S. Naval Civil Engineering Laboratory. These are described at the end of the chapter.* The experiments indicate a significant increase in the upper yield stress, but not in the lower yield stress.

3.2 Objectives of the Material Tests

In order to predict the static and dynamic resistance functions of the beams and the frames theoretically, it is necessary to know the static and dynamic stress strain curves of the steel used in the models. The objective of the material tests was therefore the determination of

* See Table 3.1

23
the dependence of the modulus of elasticity, the yield stress and the strain hardening characteristics on the strain rate. It was further of interest to determine the behavior of the material if it was strained into the yield plateau, unloaded and then reloaded at a different strain rate. Finally, the effect of annealing on the properties of the steel were determined. This permitted an evaluation of the importance of the annealing procedure, during which residual stresses in the beams and frames were relieved as far as possible.

3.3 Description of Tensile Specimens

For the material tests conducted at M.I.T., 16 specimens with an 0.1 inch by 0.5 inch cross-section were cut from solid bars of S.A.E. 1113 steel taken from the same stock as those from which the WF sections were milled. Twelve of the specimens were annealed at the same time as the model beams described in Chapter 4, so that they were subjected to essentially identical conditions. During the annealing process, the specimens were subjected to a temperature of 975° for one hour, and were allowed to cool to room temperature inside the oven for an additional three hours.

For the material tests conducted at the U. S. Naval Civil Engineering Laboratory, 19 specimens were cut from solid bars taken from the same stock as those from which the WF sections for the frame models were milled. The specimens were annealed together with the frame models in the same manner as the beam models described above.

3.4 Tensile Tests on the Instron Machine

The sixteen tensile tests at M.I.T. were conducted on an Instron machine, as shown in Figures 3.1 and 3.2. The strains were measured on a one inch gage length by means of the U-shaped extensometer shown in Figure 3.1. The applied force was measured by means of a load cell built into the Instron machine. It was calibrated before the tests were begun and after they had been completed. The graph paper on which the response was recorded automatically may be seen in Figure 3.2.
FIGURE 3.1
Instrumentation of Tensile Specimen

FIGURE 3.2
Instron Testing Machine
The four unannealed specimens and two of the annealed specimens were tested at a strain rate of $2.8 \times 10^{-5}$ sec$^{-1}$, so that the loading was essentially static. The results of these tests are shown in Figure 3.3. The remaining specimens were tested at strain rates varying from $2.8 \times 10^{-4}$ to $2.8 \times 10^{-2}$ sec$^{-1}$. The observed stress-strain curves are shown in Figure 3.4.

The mean stress-strain curves for the static tests on the annealed and unannealed specimens are shown in Figure 3.3. The graph indicates that the annealing process reduces the mean yield stress from 79.5 to 62.5 ksi and the modulus of elasticity from 29,200 to 27,900 ksi. The annealing procedure may thus be regarded as a significant aspect of the experiment.

Figure 3.5 indicates the percentage increase in the yield stress above the static yield stress as a function of strain rate. Also shown are curves for structural steel, taken from references (2) and (5). The experiments indicate a clear trend of increasing yield strength with increasing strain rate. The smaller rate of increase for S.A.E. 1113 steel, as compared to A 36 steel, may be explained by the different chemical composition and, possibly, the different grain size of the two materials. An idealized dynamic stress-strain curve is shown in Figure 3.6. The analytic expression for the increase in yield stress with strain rate, based on the straight line which best fits the data on the yield stress versus log (strain rate) plot, is also presented.

In some of the experiments, the specimens were unloaded after they had been strained into the yield plateau, then reloaded at a different strain rate. A typical test result is shown in Figure 3.7. The experiments indicate that the yield stress observed during reloading is determined by the strain rate during reloading.

3.5 Tensile Tests at the U. S. Naval Civil Engineering Laboratory

A series of 19 tensile tests on the samples described in section 3.3 has been performed on the NCEL Dynamic Testing Machine(13). The
FIGURE 3.3
STATIC TESTS ON ANNEALED AND UNANNEALED SPECIMENS
FIGURE 3.4
STRESS STRAIN CURVES FOR VARIOUS STRAIN RATES
FIGURE 3.5
INCREASE IN YIELD STRESS WITH STRAIN RATE
FIGURE 3.6
APPROXIMATION OF THE STRESS STRAIN CURVE AT ANY STRAIN RATE

\[ I = 4.33 \log \left( \dot{\varepsilon} / 2.8 \times 10^{-5} \right) \% \]
FIGURE 3.7
EFFECT OF RELOADING AT A DIFFERENT STRAIN RATE
static and dynamic testing installations are shown in Figures 3.8 and 3.9. A typical oscillograph record is shown in Figure 3.10. The results are summarized in Table 3.1. The percentage increase in the upper yield strength is shown in Figure 3.5. Because of variability in the observed mechanical properties, the observations drawn are based on average values.

The upper yield stress increases 25% as the strain rate is varied from 0.018 to 1.8 in/in/sec. For all practical purposes, the lower yield stress does not seem to change. The tensile strength at the maximum strain rate is almost equal to the static value. The stress at rupture decreases with increasing testing speed by approximately 2000 psi, but remains constant after a strain rate of 0.26 in/in/sec has been reached. The ductility of the steel increases with testing rate. The increase in total elongation ranges between 5 and 10 percent at the two highest testing rates.
FIGURE 3.8
Dynamic Test at NCEL
FIGURE 3.9
Static Test at NCEL
Figure 3.10 Typical oscillograph record of tension test at a strain rate of 0.29 in./in./sec (Specimen CS 240)
Table 3.1: Tensile Tests at NCEL

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Elastic Strain Rate</th>
<th>Strain Rate (in/in/sec)</th>
<th>Upper Yield Stress (psi)</th>
<th>Lower Yield Stress (psi)</th>
<th>Tensile Strength (psi)</th>
<th>Rupture Stress (psi)</th>
<th>Elongation (%)</th>
<th>Plastic Modulus (psix10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS 222</td>
<td>10^-5</td>
<td>-</td>
<td>63,000</td>
<td>63,000</td>
<td>75,500</td>
<td>60,000</td>
<td>18.00</td>
<td>1.2</td>
</tr>
<tr>
<td>CS 223</td>
<td>10^-5</td>
<td>0.00058</td>
<td>68,000</td>
<td>68,000</td>
<td>80,000</td>
<td>63,500</td>
<td>18.25</td>
<td>1.4</td>
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<tr>
<td>CS 226</td>
<td>10^-5</td>
<td>-</td>
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<td>78,500</td>
<td>63,000</td>
<td>17.50</td>
<td>1.3</td>
</tr>
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<td>CS 228</td>
<td>10^-5</td>
<td>-</td>
<td>65,000</td>
<td>65,000</td>
<td>77,000</td>
<td>62,000</td>
<td>17.00</td>
<td>1.3</td>
</tr>
<tr>
<td>Ave.</td>
<td>10^-5</td>
<td>-</td>
<td>66,400</td>
<td>65,600</td>
<td>77,750</td>
<td>62,100</td>
<td>17.7</td>
<td>1.3</td>
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<td>58,500</td>
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<td>50,500</td>
<td>24.75</td>
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<tr>
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<td>0.081</td>
<td>65,000</td>
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<td>51,500</td>
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<td>2.0</td>
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<tr>
<td>CS 233</td>
<td>0.019</td>
<td>-</td>
<td>67,000</td>
<td>60,000</td>
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<td>51,500</td>
<td>19.00</td>
<td>-</td>
</tr>
<tr>
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<td>0.085</td>
<td>71,000</td>
<td>67,500</td>
<td>76,500</td>
<td>58,500</td>
<td>21.00</td>
<td>2.5</td>
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<td>0.080</td>
<td>68,300</td>
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<td>54,100</td>
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<td>52,000</td>
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<td>63,000</td>
<td>21.25</td>
<td>3.9</td>
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<td>72,500</td>
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<td>50,500</td>
<td>26.50</td>
<td>2.0</td>
</tr>
<tr>
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<td>1.35</td>
<td>75,000</td>
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<td>72,600</td>
<td>59,500</td>
<td>25.7</td>
<td>2.6</td>
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<td>11</td>
<td>79,000</td>
<td>62,500</td>
<td>71,500</td>
<td>50,500</td>
<td>25.25</td>
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<tr>
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<td>15</td>
<td>80,500</td>
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<td>71,000</td>
<td>52,500</td>
<td>23.50</td>
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<tr>
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<td>-</td>
<td>88,000</td>
<td>73,000</td>
<td>82,000</td>
<td>58,500</td>
<td>24.00</td>
<td>-</td>
</tr>
<tr>
<td>CS 241</td>
<td>1.5</td>
<td>12</td>
<td>81,500</td>
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<td>59,000</td>
<td>22.75</td>
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<td>Ave.</td>
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<td>12.7</td>
<td>82,200</td>
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<td>2.7</td>
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<tr>
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<td>-</td>
<td>54,000</td>
<td>54,000</td>
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<td>50,500</td>
<td>20.00</td>
<td>1.8</td>
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<td>1.31</td>
<td>86,000</td>
<td>73,000</td>
<td>83,000</td>
<td>63,000</td>
<td>23.75</td>
<td>1.9</td>
</tr>
</tbody>
</table>

1 Strain rate in the strain hardening range
2 Test specimen not used in averages
3 Measured over a two inch gage length
Chapter 4

BEAM TESTS

4.1 Aims

The purpose of the beam tests was an investigation of the effect of strain rate on the resistance function of a simply supported statically determinate structure (as opposed to the more complex fixed base portal frame). The experimental results were compared to various theories to test the agreement in this simple case before the more difficult frame tests were performed. The beam tests also provided an opportunity to evaluate the dynamic loading machine, the deflection measuring instrument, and the associated instrumentation tests involving flexible specimens. The test series made it possible to detect flaws in the loading system and the recording equipment before the expensive frame models were tested.

4.2 Manufacture of the Beams

The beams whose behavior was investigated in these tests are 1 in 10 scale models of an 8 WF 67 prototype. They were milled from 15/16 inch square bars of SAE 1113 steel in 8 ft. lengths. The material properties are discussed in Chapter 3. Two test series were conducted. The second series was necessary to verify the extraordinary results of the first series.

In the first test series, ten beams of 19" length were cut from the longer sections. Several considerations influenced this choice of length:

i) the order of magnitude of the expected deflections at the center of the beam was chosen so that it was readily measurable;

ii) the beam had to be long enough so that a reasonable load was capable of producing plastic deformation;

iii) lateral buckling would become a problem as the length increased so that larger forces would have to be resisted by the lateral supports.
Four sets of stiffeners machined from 1/8" thick steel were silver soldered to the web and flange of the beam at the locations shown in Figure 4.2. These served to strengthen the beam where the load and the reactions were applied. The reactions were transmitted to the beam by the two blocks on the lower flange which rest on knife edges. One end of the loading beam was provided with a knife edge which fits into the block on the upper flange. Then the bearing plates were silver soldered to the beams. After all silver soldering had been completed, the beams were annealed as described in section 3.2. The second test series is described later.

4.3 Support System, Loading Beam, and Measurement of Deflection

The design of the support system was governed by three requirements:

i) to provide as nearly as possible a hinge support at one end and a roller support at the other end of the beam;

ii) to provide enough lateral support to prevent lateral torsional buckling, i.e., to limit lateral deflections to a few thousandths of an inch;

iii) to provide a means of adjusting the elevation of the beam, so that the piston stroke of the dynamic loading machine could be varied.

The overall dimensions of the support system are shown in Figure 4.1. Several different views of the support system are presented in the photographs of the test setup, Figure 4.3 to Figure 4.5. The level of the beam was adjusted by turning the large nuts on the threaded rods. The beam was supported by means of knife edges made from high strength tool steel. One of the knife edges was attached to a cart supported by 4 ball bearings. This provided a roller type of support at one end. The lateral support was easily adjusted since the plates are slotted and are fixed in the desired position by the tightening of bolts.

The loading beam was constructed from a 7 inch piece of the model I beam so as to keep its mass as small as possible. Four sets of stiffen-
FIGURE 4.1
BEAM SUPPORT SYSTEM
STIFFENERS AND BEARING PLATES SILVER SOLDERED TO BEAM

ELEVATION OF MODEL BEAM
CROSS SECTION: 1 IN 10 SCALE MODEL OF 8 WF67 SECTION

ELEVATION OF LOAD DISTRIBUTION BEAM
CROSS SECTION: AS FOR MODEL BEAM

FIGURE 4.2
GEOMETRY OF MODEL BEAM AND LOAD DISTRIBUTION BEAM
FIGURE 4.3
Typical Beam before Loading

FIGURE 4.4
Typical Beam after Loading
FIGURE 4.5
Overall Views of Beam Test Stand
ers were silver soldered in the locations shown in Figure 4.2. A bearing plate was silver soldered at the center of the top flange where the load is applied. A knife edge and another bearing plate were silver soldered to the bottom flange. The lower bearing plate rested on a 3/8" round bar, providing a roller type support.

The deflections were measured by means of the potentiometer mentioned in section 2.3.4. The potentiometer is a very delicate instrument. The potentiometer rod is capable only of axial motion. A very slight amount of lateral motion will cause internal damage. The rod was attached to the beam by means of the lever arm system shown in Figure 4.4. This system essentially prevented the application of horizontal forces on the potentiometer rod for the small range of deflections to which the beams were subjected.

4.4 Testing Procedure

The base plate was adjusted so that it was level and at the correct height. The plates providing lateral support were loosened and the model beam set on the knife edge supports. The loading beam was then placed on top of the model beam. The system was adjusted so that it was in the correct position relative to the load cell. Then the beam was fixed in place by means of clamps at each end. Metal strips .005 inch thick were placed between the lateral support plates and the beam. The lateral support plates were set tight against the metal strip and fixed in position. Then the metal strips were removed. This procedure permitted adequate lateral support, and at the same time prevented wedging of the beam between the plates. The lever arm of the deflection measuring device was attached to the lower flange at the center of the beam and the potentiometer was properly positioned. Finally, the clamps were removed from the ends of the beam and the load applied as described in section 2.4.1.

Figures 4.3 and 4.4 show the model beam in the support system. The photographs were taken during an actual test. Figure 4.5 presents overall views of the experiment.
4.5 Test Results

Two of the 10 beams of the first series, No. 1 and 2, were tested statically. The load deflection curves are presented in Figure 4.7. In the elastic region, the behavior of the two beams is in good agreement. There is some difference in the behavior in the plastic region. The plastic deformation occurred throughout the central third of the beam, which assumes the shape of a circular arc. Plastic deformation in the outer thirds of the span was restricted to the immediate vicinity of the third points.

The eight remaining beams were tested dynamically. The results of one test were lost because the oscilloscope did not trigger. Another beam was accidentally tested at too small a load (1200 pounds maximum) so that the beam deformed only very slightly into the plastic region. The results are not presented because they are not suitable for a study of strain rate effects. The remaining six beams were tested in groups of two with different loading functions which were obtained by using orifice areas of 0.546, 0.472, and 0.096 square inches.

Beams 3 and 4 were tested with an orifice area of 0.546 square inches and a nominal gas pressure of 120 psi. The oscilloscope output for these tests is presented in Figure 4.6. On each photo, the upper curve represents the output of the load cell, the lower curve the output of the deflection potentiometer attached to the midpoint of the beam. Deflection measurements after the maximum deflection is reached are not regarded as reliable because of play in the lever system. The response is also shown graphically in Figure 4.8. The load-time functions differ slightly. The rise time for an equivalent bilinear load pulse would be of the order of 4 milliseconds. It is seen that the effect of this slight difference on the maximum deflection is considerable: beam 3 deflects 0.75 inches, beam 4 only 0.55 inches.

Beams 5 and 6 were tested with an orifice area of 0.742 square inches and a nominal gas pressure of 120 psi. The oscilloscope output for these tests is presented in Figure 4.6. The same output is presented graphically in Figure 4.9. It is noted that the load-time functions for the two tests are essentially identical. The rise time for an equivalent
FIGURE 4.6
Oscilloscope Output for Beams 3 to 6.
FIGURE 4.7
STATIC BEHAVIOR OF BEAMS 1 AND 2
FIGURE 4.8
DYNAMIC BEHAVIOR OF BEAMS 3 AND 4
FIGURE 4.9
DYNAMIC BEHAVIOR OF BEAMS 5 AND 6
FIGURE 4.10
BEHAVIOR OF BEAMS 7 AND 8
bilinear load pulse would be of the order of 6 milliseconds. The deflection-time curves for the two beams differ very slightly. The maximum deflection of the beam 5 is 0.305 inches, that of beam 6 is 0.320 inches.

Beams 7 and 8 were tested with an orifice area of 0.096 square inches and a nominal gas pressure of 130 psi. Due to the very large rise time, which is of the order of 100 milliseconds, the response of the beams as presented in Figure 4.10 is essentially static as far as body forces are concerned. It is, however, not static as far as time-dependent plastic deformations are concerned. This is clearly shown on the deflection-time diagram, which indicates that the deflections continue to increase long after the load has reached a constant value. The diagram is characterized by a rapid increase in the deflection once the beam becomes plastic, which contrasts with the smooth curves observed for the more rapidly loaded beams. The difference in the maximum deflection of beams 7 and 8 appears to be large. It is, however, readily explained by a very small change in the yield plateau shown in Figure 4.7. This confirms the conclusion from the static tests, i.e., that there is a slight variation in the behavior of different beams in the plastic region.

4.6 Discussion of Test Results

The experimental observations are compared to two significantly different mathematical solutions. The most significant characteristics of these methods are as follows:

**Method 1:** The details of this solution are described in Appendix A. The beam is represented by an equivalent one degree of freedom system whose deflection equals the midspan deflection of the actual beam. The mass of the equivalent system is obtained from that of the actual beam through multiplication with a load-mass factor, as suggested by Biggs (8). The mass of the loading beam is accounted for. The average static resistance function of the beam, as indicated in Figure 4.7, is used as resistance function for the equivalent system when strain rate effects are neglected. A second solution, accounting for strain rate effects, is also obtained.
The ordinates of the resistance function are then increased in proportion to the increase in the yield stress, as determined by the strain rate at the time of yielding. An estimated dynamic resistance function is shown in Figure 4.7.

**Method II:** The details of this solution are described in Appendix B. The actual beam is subdivided into a number of massless segments, connected by flexible joints. The mass of the beam is lumped at the joints. The moment-curvature relationship of the beam is computed by dividing the cross-section into a number of segments, assuming a linear variation of strain over the depth of the section and determining the corresponding stresses from the stress-strain curve of the steel as determined in tensile tests. The strain rate is accounted for through its effect on the stress-strain curve, as discussed in Chapter 3. This solution also accounts for the mass of the loading beam.

**Beams 1 and 2:** The static load-deflection behavior of beams 1 and 2, as shown in Figure 4.7, may be compared to the curve predicted by the computer program in Method II above. For this purpose, the program is used with a very long rise time. If a yield stress of 62,500 psi is assumed, the predicted load-deflection curve is essentially bilinear. The yield load of 1250 pounds is reached with a deflection of 0.17 inches. The agreement between theory and experiment is thus good in the elastic range. While the difference in the plastic range does not appear to be large, it has a very significant effect on the dynamic response for the particular load function used in the dynamic experiments. This is discussed at the end of this section.

**Beams 3 and 4:** Consider the behavior of beams 3 and 4, as shown on Figure 4.8. Solution I without strain rate effects is in excellent agreement with the experimentally observed deflection time curves. Both the maximum deflection and the time of maximum response are accurately predicted. The strain rate at yielding is found to be 1.20 sec\(^{-1}\) for beam 3 and 0.85 sec\(^{-1}\) for beam 4. This corresponds to a 19% increase in the yield stress of the steel according to the tests on the Instron machine. The corresponding dynamic resistance function of the beam is shown in Figure 4.7. If solution I is repeated, using the dynamic
resistance function, the predicted maximum deflections are 50% in error, while the time of maximum response is 30% in error. Solution II, which is evaluated for an equivalent bilinear load function - while solution I is evaluated for the actual load function - does not yield a reasonable prediction of the dynamic behavior. This is attributed mainly to the fact that this solution does not make use of the exact resistance function of the beam, as indicated in the discussion of the static tests. The following conclusions may be drawn from the tests on beams 3 and 4:

1) The resistance function of the beams is not a function of the strain rate

2) An accurate prediction of the dynamic deflections of the beam by means of a single degree of freedom system is possible if the exact resistance function of the beam is considered.

Beams 5 and 6: Consider the behavior of beams 5 and 6, as shown on Figure 4.9. Solution I without strain rate effects is again in good agreement with the experimentally observed deflection-time curves. The strain rate at yielding is $0.55 \text{ sec}^{-1}$. This corresponds to an 18% increase in the yield stress of the steel. If solution I is repeated, using the dynamic resistance function, the predicted maximum deflection is 30% in error, while the time of maximum response is 20% in error. Solution 2, both with and without strain rate effects, does not yield a reasonable prediction of the dynamic behavior. The conclusions which may be drawn from the tests on beams 5 and 6 are the same as those for the tests on beams 3 and 4.

Beams 7 and 8: The behavior of beams 7 and 8, as shown in Figure 4.10, is not influenced by body forces. The theoretical prediction of the deflections is obtained by reading on Figure 4.7 the deflection which corresponds to the load acting on beams 7 or 8 at a particular instant. Agreement within the elastic range is good. In the plastic range, the theoretical solution assumes a constant deflection as soon as the load becomes constant. The experimental observations show a steady increase in the deflections. This indicates that some of the
plastic deformation, as might be anticipated, is time-dependent, i.e. it occurs by a flow process. This flow process will not occur in the short time before beams 3 to 6 reach their maximum deflection. The use of resistance functions based on static rests or computed from static stress-strain curves must thus be regarded as an approximation in the theoretical analysis. These considerations are valid regardless of whether the strain rate affects the yield stress or not.

Summary

The dynamic tests described in this chapter have been designed so that the deflection response is very sensitive to strain rate effects. The dynamic load function is chosen so that the maximum load of approximately 1320 pounds corresponds to the beginning of the yield plateau of the resistance function of the beam, as shown in Figure 4.7. If there is no strain rate effect, the dynamic response of the beam will proceed well into the plastic range; i.e., large deflections will be observed. If the strain rate effect changes the resistance function as shown in Figure 4.7, the applied maximum load is 16% less than the dynamic yield load. The portion of the elastic strength of the beam which is in excess of the applied load is then sufficient to resist the dynamic effects without considerable plastic deformation, so that the observed deflections will be considerably smaller than if there is no strain rate effect. This is demonstrated by solutions IB for beams 3 and 4.

In view of the sensitivity of the tests and the reproducibility of the results, there appears to be little doubt that under the stress conditions existing in the beam tests, the yield stress of SAE 1113 steel is not affected by strain rates of the order of 1.0 sec$^{-1}$. Since this result was somewhat unexpected, it was decided to perform a second test series to confirm the observed beam behavior.

4.7 Control Test Series

The control test series consisted of three static tests on beams 9 to 11 and three dynamic tests with an orifice area of 0.546 square inches on beams 12 to 14. These experiments were conducted three months after the original test series, and different personnel were employed.
FIGURE 4.11
STATIC BEHAVIOR OF BEAMS 9, 10 AND 11
FIGURE 4.12
DYNAMIC BEHAVIOR OF BEAMS 12, 13 AND 14
The load cell and deflection potentiometer were recalibrated. The beams were fabricated from 1 in 10 scale models of 8 WF 67 beams which had been left over from the frame tests. The annealing procedure and all testing arrangements were identical to those for the first tests series.

The three static tests are in good agreement with each other. The yield plateau, as shown in Figure 4.11, is slightly flatter than that for beams 1 and 2, but the difference is not very significant. The results of the dynamic tests are presented in Figure 4.12. The reproducibility of both the load functions and the observed deflection-time curves is good if one keeps in mind the large variety of parameters affecting the response in this experiment. Solution I without strain rate effects yields good predictions of the maximum deflection and the time at which it occurs. The strain rates at yielding are 0.85, 0.75, and 1.00 sec\(^{-1}\) for beams 12, 13, and 14 respectively. This corresponds to an 18% increase in the yield stress. If solution I is repeated, using the dynamic resistance function, the predicted maximum deflections as shown in Figure 4.12 are 50% in error, while the time of maximum response is 30% in error. Generally, the control tests lead to the same conclusion as the original test series.

A second series of control tests was performed still later, using models manufactured out of SAE 1020 instead of SAE 1113 steel. The results are presented in Appendix D.
5.1 Aims

Steel portal frames are widely used in normal and in blast resistant construction. It is therefore of importance to verify that mathematical methods of predicting the behavior of portal frames are reliable. One of the major uncertainties in the theoretical analysis is the dependence of the resistance function and the buckling characteristics of a frame on the strain rate during a dynamic response. In addition, some flexibility may exist in seemingly rigid base and knee connections, affecting not only the dynamic but also the static behavior of the structure.

The aim of these tests was therefore an investigation of the static and dynamic behavior of portal frames, with special emphasis on the effect of the strain rate during the dynamic tests. The experimental observations were to be compared to theoretical predictions as derived in appendix C. The tests had to be arranged so that the effect of dynamic loading on the buckling characteristics could be observed. Generally, it had to be determined whether the conclusions reached for this more complex structure were the same as those reached for the simple beams in Chapter 4.

The conclusions reached from the frame tests described in this chapter are compared to those reached from large scale tests at the U. S. Naval Civil Engineering Laboratory.

5.2 Manufacture of the Frames

The model frames were built up out of 1 in 10 scale models of 8 WF 31 and 8 WF 67 steel beams. The 8 WF 67 is a compact section which can be deformed well into the plastic range before local buckling occurs. The 8 WF 31, on the other hand, buckles locally shortly after the yield moment is reached. The two sections were combined in four different manners, yielding frame types I to IV as shown in Table 5.1. All frames were 12.2 inches high, with a span of 16 inches, as shown in
Figure 5.1. All base connections were as shown in Figures 5.1 and 5.4. Four frames of each type were constructed and labelled A, B, C and D.

The girder and columns were cut to the required length and shape, as shown in Figure 5.1. Stiffeners and base plates were machined to the required dimensions. The elements were then silver soldered together on a jig. Preliminary tests at M.I.T.\(^{(7)}\) had indicated that this type of connection, which is considerably less expensive than microwelding, would be satisfactory. A static test on frame IA indicated conclusively that the column to girder connections could not develop the ultimate capacity of the 8 WF 67 section. To increase the strength at the joints, a steel rod and a cover plate were welded to the tension flanges at the locations indicated in Figure 5.1. The joints then proved to be sufficiently strong to develop the ultimate moment capacity of the members. No difficulties were experienced at the base plates.

Table 5.1: Geometric Properties of Frames

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>Columns</th>
<th>Girder</th>
<th>Column Stiffness</th>
<th>Girder Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>8 WF 67</td>
<td>8 WF 67</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>8 WF 31</td>
<td>8 WF 31</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>8 WF 31</td>
<td>8 WF 67</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>8 WF 67</td>
<td>8 WF 31</td>
<td>0.32</td>
<td></td>
</tr>
</tbody>
</table>

The assembled frames, together with a number of tensile specimens, were annealed at a temperature of 975° F for one hour. They were allowed to cool to room temperature inside the oven for an additional three hours. A photograph of the 16 frames is presented in Figure 5.2.

5.3 Test Stand

In order to be able to test the frames under controlled conditions, it is necessary to
i) provide a means of attaching the column bases to supports which are essentially fixed
ii) provide a means of measuring one column reaction
iii) prevent significant displacement of the frame perpendicular to its plane.
ALL CONNECTIONS SOLDERED UNLESS OTHERWISE SHOWN

PLATE WELDED ON

ROD WELDED ON

CORNER DETAIL

BASE DETAIL

FIGURE 5.1
GEOMETRY OF A TYPICAL FRAME
FIGURE 5.2
Photograph of 16 Model Frames

FIGURE 5.5
Photograph of Test Stand
FIGURE 5.3
FRAME TEST STAND
SECTION

TURNBUCKLE LOAD CELL

0-06"

0.188" DIAMETER PIN

ANCHOR BLOCK

CBG-7 STRAIN GAGE

500±3, G.E. 3.49±1%

PLAN

FIGURE 5.4
COLUMN SUPPORT WITH REACTION MEASURING DEVICE
The test stand designed for the experiments described in this chapter is shown in Figure 5.3. The reaction measuring system is shown in detail in Figure 5.4. Mounted on the test stand is an angle supporting the potentiometer which measures the deflections. In order to protect the very sensitive potentiometer from damage due to lateral forces on its rod, it was decided not to connect the rod physically to the frames. Because the frame pushes the potentiometer rod, a record of displacement as a function of time was obtained only until the maximum deflection was reached. Figure 5.5 presents a photograph of the test stand just before the load is applied to a frame.

5.4 Testing Procedure

The static and dynamic tests on the model frames were carried out in the following manner:

i) Static Tests:

1. Before the test was conducted, aluminum loading blocks 3/4" x 3/4" x 1/4" were glued to the corner of the frame where the load is applied. These blocks prevented the column flange from buckling at the load point and yet permitted the column to rotate.
2. The column bases of the model were bolted down to their respective supports.
3. The restraining pulleys were brought to bear against the girder web.
4. The potentiometer rod was moved into position against the corner of the frame. An Ames dial gage was mounted so as to measure the deflection of the same point.
5. The output from the three transducers was set at zero on the oscilloscopes.
6. The loading rod was brought into position and gas pressure was introduced into the cylinder in increments of 2 to 10 psi.
7. For each increment in pressure, readings were taken from the transducers and the dial gage.
8. Loading was continued until the maximum travel of the loading rod was achieved, thus well into the plastic range.

The static tests served to test the loading procedure as well as the reliability of the supporting devices and the measuring equipment. The results of these tests also served as a basis of comparison for the dynamic tests.

ii) Dynamic Tests

The model was placed in the testing frame and readied for loading in a manner similar to the static experiments. The loading rod was brought into position and the output from the three transducers set at zero values. The dynamic load was applied as described in section 2.4.1. For dynamic tests, the recording of measured forces and displacements was performed automatically by the oscilloscope cameras. After the dynamic test had been completed, the load was removed and final oscilloscope zero readings taken.

5.5 Experimental Results

Of the 16 frames built for this test series, 12 yielded useful information. The following frame tests will not be discussed further:

i) Frame IA: failure at the knees because silver soldering alone did not develop the ultimate moment capacity of the sections.

ii) Frame IIIB: triggering circuit did not activate oscilloscopes.

iii) Frame IIIC: improper machining of one column. Flange split from web during dynamic test, leading to a spectacular failure.

iv) Frame IVB: triggering circuit did not activate oscilloscopes.

The static and dynamic tests will be described separately.

5.5.1 Static Tests - One frame of each type was tested statically. A typical frame after testing is shown in Figure 5.6. A detail of a buckled knee is shown in Figure 5.7. The static load deflection curves of the four frame types are presented graphically in Figures 5.8 and 5.9. Frame ID did not exhibit any signs of local buckling. Frames IIA, IIIA, IVA all were affected by some degree of local buckling. The buckling loads are indicated in Figures 5.8 and 5.9.
FIGURE 5.6
Typical Frame after Testing

FIGURE 5.7
Detail of Buckled Knee
FIGURE 5.8
STATIC FRAME TESTS
FIGURE 5.9
STATIC FRAME TESTS
In frame II, local buckling initially occurred in both the column and the girder at the knee. At a slightly higher load, the column also buckled at the base. Both flange buckling and web crippling were evident. Once a load of 650 pounds had been reached, the deflection increased continuously at constant load until the load was removed. Frame III behaved in a similar manner, except that the 8 WF 67 girder did not buckle. In frame IV, buckling occurred in the compression flanges of the 8 WF 31 girder near both knees. The web of the girder was crippled.

5.5.2 Dynamic Tests - In the dynamic tests, the applied load, lateral deflection and support reaction were recorded by means of cameras attached to the single sweep oscilloscopes. Typical output is presented in Figures 5.10 and 5.11. The grid shown on the photographs is one centimeter square. The horizontal scale in all cases is 10 milliseconds per centimeter. The vertical scale for the applied load (upper beam) is 420 pounds per centimeter, that for the displacement (lower beam) is 0.305 inches per centimeter. The vertical scale for the reaction (lower photo) is 143 pounds per centimeter.

Frames IB and IC were tested with an orifice area of 0.546 square inches, yielding a nominal rise time of 7 milliseconds. Both the load-time and deflection-time curves of the two frames are in good agreement, as shown in Figure 5.12. The maximum deflections are 0.94 and 1.09 inches respectively, the time required to reach the maximum deflection is 28 and 24 milliseconds respectively.

Frames IIB and IIC were also tested with an orifice area of 0.546 square inches. The nominal rise time is 7 milliseconds. The load-time and deflection-time curves for the two frames are again in good agreement, as shown in Figure 5.13. The maximum deflections are 0.85 and 0.91 inches respectively, the time required to reach the maximum deflection is 28 milliseconds in both cases. Frame IID was tested with an orifice area of 0.386 square inches. The load-time function is no longer bilinear. The dynamic effects are reduced considerably: the maximum deflection is only 35% of that for frames IIB and IIC, and is reached in 16 instead of 28 milliseconds. The frame continued to deform at a constant load for several seconds.
FIGURE 5.10: Oscilloscope Output for Frames I and II
FIGURE 5.11: Oscilloscope Output for Frames III and IV

Load and Displacement

Reaction

FRAME IIID

Load and Displacement

Reaction

FRAME IVD
FIGURE 5.12
DYNAMIC TESTS ON FRAMES I
FIGURE 5.13
DYNAMIC TESTS ON FRAMES II
FIGURE 5.14
DYNAMIC TESTS ON FRAMES III
FIGURE 5.15
DYNAMIC TESTS ON FRAMES IV
Frame IIID was tested with an orifice area of 0.546 square inches. The load-time curve is bilinear and the nominal rise time is 7 milliseconds. A maximum deflection of 1.07 inches is reached after 30 milliseconds as shown in Figure 5.14. This is the only frame of type III that was tested dynamically with success.

Frame IVC was tested with an orifice area of 0.546 square inches and a nominal rise time of 7 milliseconds. Frame IVD was tested with an orifice area of 0.386 square inches. The load-time function is not bilinear. The behavior of the two frames, as shown in Figure 5.15, is similar to that of frames IIC and IID. Frame IVC reaches a maximum deflection of 0.90 inches in 20 milliseconds, frame IVD a maximum deflection of 0.29 inches in 12 milliseconds. Frame IVD continued to deform for several seconds.

5.6 Discussion of Test Results

The experimental observations are compared to the predictions of the theories presented in Appendix C. The static tests are correlated with a theory accounting for the flexibility of the knee and of the base connection, as discussed in section C.2. The dynamic tests are correlated with the predictions of an equivalent one degree of freedom system whose resistance function is the experimentally determined static load-deflection curve. Strain rates, and their effect on the strength as observed in a tension test, are computed as described in section C.3.

5.6.1 Static Tests - The agreement between theory and experimental outcome is excellent in all four cases. Frame II, as expected, has the best moment restraint at the column bases: the effective length of the column is increased by only 3%. Frame IV, which has stiff columns and a flexible girder, exhibits the least effective base restraint: the effective length of the column is increased by 25%. The increases for frames III and I are intermediate: 5 and 8% respectively. These figures compare to a value of 25% found in large scale tests. Buckling affects the load-deflection curve only slightly. The effect is strongest
for frames II, where both the columns and the girder have the 8 WF 31 cross section. The agreement between the experimental observations and the predictions of the theory presented in section C.1, which does not account for the base and knee flexibilities, would have been unsatisfactory.

5.6.2 Dynamic Tests — The experimentally observed dynamic behavior is compared to theoretical predictions based on a one degree of freedom system. It is assumed that the strain does not affect the resistance function of the frame. This assumption led to good predictions for the beam tests. If it also does so for the frame tests, the conclusions drawn from the beam tests will have been confirmed.

It is not necessary to describe the agreement between the theoretical and experimental deflection-time curves for each frame individually. The theoretical curves presented in Figures 5.12 to 5.15 generally predict the frame behavior accurately. The maximum deflections differ insignificantly from those observed experimentally. The theoretically predicted maximum response generally occurs a few milliseconds before the experimentally observed maximum. Two theoretical curves are presented for frames IIB and IIC: one is based on the actual static resistance function and predicts too large a deflection. The other is based on the theoretically predicted static resistance function, which differs from the actual one only insofar as the reduction in the load carrying capacity due to local buckling is neglected. The second solution is in good agreement with the experimental deflection-time curve. This appears to indicate that the buckling which occurs in the static tests does not occur in the dynamic tests in the short time that elapses before the maximum deflection is reached.

The strain rates at yielding in the various frames vary between 0.32 and 1.90 sec\(^{-1}\), the corresponding percentage increase in the tensile strength varies from 17.7 to 21.0%. These increases are significantly larger than the errors that may exist in the experimental technique. The fact that the statically observed resistance function, corrected for buckling as described above, rather than an estimated
dynamic resistance function with a 20% higher yield plateau, leads to
good correlation with the experimental deflection-time curve, indicates
clearly that the strain rate does not have a significant effect on the
resistance function of frame models manufactured out of SAE 1113 steel.

5.7 Comparison between Model and Large Scale Tests

It has been discussed in Chapter 1 that simultaneous modeling
of inertia body forces and strain rate-effects in steel structures is
technologically very difficult. No attempt has therefore been made to
model at a reduced scale the frame tests conducted at the U. S. Naval
Civil Engineering Laboratory(11). Instead, the general conclusions
of the two test series are compared point for point.

i) It is concluded in reference (11) on p. 33 that "if the
cross section of the girder is equal to or slightly
different from the column, the plastic hinges may be ex-
pected to form where the columns connect to the girder,
and at the bases; a dynamic analysis by a simple spring-
mass system is then justified." The conclusion is con-
firmed by the model test series presented in Chapter 5
of this report.

ii) It is concluded in reference(11) on p. 34 that "the theo-
retical static analysis can be conveniently used to pre-
dict the static behavior of a fixed-base rigid frame
subjected to a uniformly distributed load on one column".
The present test series permits a similar conclusion for
a concentrated lateral load acting horizontally at the
level of the girder.

iii) It is further concluded on p. 34 that "the frames had
relative fixities of 80% for the loaded column and 83%
for the unloaded column". The model frames had relative
fixities of 75, 92, 95 and 97%.

iv) It is concluded on p. 34 that "the general appearance of
the failure modes of frames subjected to static and dynamic
loads were about the same". This is also true for the
model tests.
v) The model test series leads to the conclusion that the resistance function is essentially independent of strain rate. The large scale tests (reference \textsuperscript{(11)}, p. 35) lead to the conclusion that "for A-7 mild steel, with a strain rate of about 0.2 in/in/sec., the increase in yield point may be taken as 33\% and the increase in ultimate strength may be taken as 11\%". It is not possible, without further tests, to determine whether this difference in conclusions is due to differences in the types of test performed, or whether it is caused by the different properties of the two steels used in the experiments. For the beam tests, this point is discussed further in appendix D.
Chapter 6

GENERAL CONCLUSIONS

The good reproducibility of both the beam and the frame tests conducted for this project, as well as the agreement between theoretical predictions and the experimentally observed behavior, clearly demonstrate the usefulness of small scale models for investigations of the static and the dynamic behavior of steel structures.

The theoretically predicted and experimentally observed static yield loads for the beams and the frames are in good agreement. The model tests emphasize the important effect of the flexibility of the knee connections and of the degree of fixity at the column bases on the stiffness of the frames. The load-time function employed in the dynamic beam and frame tests is considered to yield a very sensitive indication of the effect of strain rate on the resistance function of the models. Some of the instrumentation problems which affect the reliability of dynamic tensile tests are eliminated in the bending tests. The experimental observations presented in chapters 4 and 5 indicate that the resistance functions of the SAE 1113 steel models are essentially independent of the strain rate. The resistance function of the SAE 1020 beam models described in appendix D is dependent on the strain rate. The results of the dynamic tests for frame II seem to indicate that the inelastic local buckling which takes place during the static tests does not occur in the dynamic tests until some time after the maximum deflection has been reached. Further tests should be performed to substantiate this observation.

On the basis of the tests described in this report, the following design criteria are proposed:

1. The dynamic response of simply supported elastoplastic steel beams loaded at the third points can be predicted accurately by means of an equivalent single degree of freedom system.
2. The increase in the resistance of the beams due to strain rate effects is dependent on the particular steel out of which the beams are manufactured. For strain rates of the
order of 1.0 inch/inch/second, the dynamic resistance of SAE 1020 steel beams shows an increase of 15 to 20% over the static resistance, while the resistance of SAE 1113 beams shows no significant increase.

3. The flexibility of the knee connection and the degree of end fixity of the frame columns should be taken into account in the theoretical static analysis of a fixed base rigid steel frame. If this had not been done, errors of the order of 50% would have been made in the prediction of the flexibility of the frames described in chapter 5.

4. It is difficult to construct frames so that the base of the columns is perfectly restrained against rotation. The elaborate precautions taken during this research project lead to end fixities of 75, 92, 95 and 98 percent.

5. On account of local buckling, the experimental static load-deflection curve of the frames of type II deviated significantly from the theoretically predicted curve where buckling was neglected. The possibility of buckling should be accounted for in the theoretical static analysis.

6. In a fixed base rigid steel frame subjected to a horizontal load at the level of the girder, plastic hinges form at the knee and at the base of the columns. The dynamic response of the frame can be predicted by means of a simple spring-mass system as described in appendix C.

A major portion of the total effort spent on this project was diverted to the development of the dynamic loading machine. This was necessitated by the difficulties experienced in obtaining the desired short rise times. The number of frame and beam tests conducted for the project, 38, was considerably less than the number that might be performed during an equivalent period if the testing facilities were available from the outset. During subsequent research efforts in the same area, it would therefore be possible to test a wide variety of geometric configurations under a number of different loading conditions, in considerably shorter time and at significant reductions in cost as compared to large scale tests.
Appendix A

SINGLE DEGREE OF FREEDOM ANALYSIS FOR A
BEAM SUBJECTED TO THIRD POINT LOADS
AND STRAIN RATE EFFECTS

A.1 Method of Solution

Consider a beam of constant cross-section, loaded at the third points and simply supported at the ends, as shown in Figure A.1. It is well known from the theory of the dynamic behavior of structures (8) that the dynamic behavior of this beam may be approximated by that of the one degree of freedom system which is also shown in Figure A.1. This system is selected so that its deflection in the x-direction equals the vertical deflection of the beam at midspan. It is shown by Biggs (8) on p. 208 that the characteristics of the equivalent system may be determined by multiplying the actual mass $M_b$ of the model beam and $M_L$ of the loading beam by the appropriate load-mass factors, as given in the table on p. 209. The load applied to the equivalent system, as well as its stiffness, are the same as those of the actual structure. For the beams described in Chapter 4, we have

$$M_b = \frac{1.28}{32.2 \times 12} = 0.00332 \text{ lb sec}^2/\text{inch}$$

$$M_L = \frac{0.61}{32.2 \times 12} = 0.00158 \text{ lb sec}^2/\text{inch}$$

The load is not measured at the end of the load cell, but rather at a distance of 2.5 inches from the end. The weight of the load cell between the location of the strain gages and the end of the cell is 0.18 pounds. The mass $M_c$ of the cell is thus

$$M_c = \frac{0.18}{32.2 \times 12} = 0.00046 \text{ lb sec}^2/\text{inch}$$

To compute the mass $M_e$ of the equivalent system, it will be assumed that one half of the mass $M_L$ of the load beam and $M_c$ of the load cell is concentrated at each third point. The equivalent mass is computed
ACTUAL SYSTEM

EQUIVALENT SYSTEM

FIGURE A.1
IDEALIZATION OF SIMPLE BEAM
as follows:

Table A-1: Computation of Effective Mass

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Distributed Mass</th>
<th>Third Point Mass</th>
<th>Total $M_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load-Mass Factor</td>
<td>Load-Mass Factor</td>
<td>$M_e$ lb sec$^2$/inch</td>
</tr>
<tr>
<td>Elastic</td>
<td>0.60 0.00200</td>
<td>0.87 0.00178</td>
<td>0.00378</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.56 0.00186</td>
<td>1.00 0.00204</td>
<td>0.00390</td>
</tr>
<tr>
<td>Average</td>
<td>0.00193</td>
<td>0.00191</td>
<td>0.00384</td>
</tr>
</tbody>
</table>

The average value of 0.00384 lb sec$^2$/inch is used in the computations. The dynamic equilibrium of the equivalent system is given by

$$M_e A + R = P$$  \hspace{1cm} (A.1)

where $A$ is the acceleration of $M_e$ and where the resistance $R$ is given as a function of the displacement $Y$ by the experimentally observed static resistance function if there is assumed to be no strain rate effect. This is discussed further in section A.2. The load $P$ is known as a function of time $t$ from the load cell output.

The deflection is computed as a function of time by means of a numerical integration procedure, using the following steps:

i) Suppose that the deflection and acceleration at time $t$ are given by $Y_j$ and $A_j$. If the deflection $Y_{j-1}$ at time $(t-dt)$ is known, the deflection $Y_{j+1}$ at time $(t + dt)$ may be computed from the formula

$$Y_{j+1} = 2Y_j - Y_{j-1} + A_j(dt)^2$$ \hspace{1cm} (A.2)

ii) The resistance $R$ at time $(t + dt)$ may be determined from the load-deflection diagram of the beam (Figures 4.7 and 4.11) once the deflection $Y_{j+1}$ has been computed.
iii) Since the equivalent mass $M_e$ and the load $P$ at time $(t + dt)$ are known, the acceleration $A_{j+1}$ at time $(t + dt)$ may be computed from formula (A.1).

iv) All the required information is now known at time $(t + dt)$, and the integration procedure may be repeated to yield similar information for time $(t + 2dt)$, etc.

v) The integration procedure is not self-starting. Since the load at time 0 is zero, the deflection $Y_1$ at time $dt$ is computed by interaction as follows: compute $A_1$ on the assumption that $R$ is zero at time $dt$. Compute the deflection

$$Y = \frac{1}{6} A_1 (dt)^2$$

Use $Y_1$ to compute $R$ at time $dt$ and continue the iteration until it has converged sufficiently.

vi) In the elastic range, the stiffness of the beams is 7700 pounds per inch. The natural period is thus

$$T = 2\pi \sqrt{\frac{0.00384}{7700}} = 4.45 \times 10^{-3} \text{ seconds}$$

The time increment $dt$ is therefore chosen as 0.5 milliseconds.

A.2 Strain Rate Effects

The load-deflection curve for the beams, as determined in static tests, does not account for the effect of strain rate on the material properties. In order to account for strain rate effects, it is necessary to compute the strain rate at the time when the beam just becomes plastic. This computation can be reasonably approximate, since it is the logarithm of the strain rate, rather than the strain rate itself, which is proportional to the increase in yield stress.

The deflection of the equivalent one degree system is equal to the midspan deflection of the actual beam. If the beam were statically loaded, its midspan deflection could readily be computed as
\[ Y = \frac{23}{1296} \frac{PL^3}{EI} \]  
(A.3)

where \( E \) is the modulus of elasticity and \( I \) the moment of inertia. The strain in the extreme fiber at midspan is given by

\[ \varepsilon = \frac{Md}{2EI} \]  
(A.4)

where \( M \) is the moment at midspan and \( d \) the depth of the section. If inertia body forces are neglected in this approximate computation, expression (A.4) may be written

\[ \varepsilon = \frac{PLd}{12 EI} \]  
(A.5)

Eliminate \( P \) between expressions (A.3) and (A.5):

\[ \varepsilon = \frac{1296}{12 \times 23} \frac{Yd}{L^2} \]

Since \( d = 0.905 \) inches and \( L = 18 \) inches, this reduces to

\[ \varepsilon = 0.013 \ Y \]  
(A.6)

Since the deflection \( Y_j \) at yielding and the deflection \( Y_{j+1} \) at time \( dt \) after yielding are known from the solution described in section A.1, the strain rate at yielding may be computed as

\[ \dot{\varepsilon} = 0.013 \frac{Y_{j+1} - Y_j}{dt} \]  
(A.7)

According to the tensile tests performed at M.I.T., as described in Chapter 3, the yield strength is given as a function of the strain rate by the expression

\[ f_y = f_{yo} \left[ 1 + 0.0433 \log \frac{\dot{\varepsilon}}{2.8 \times 10^{-5}} \right] \]  
(A.8)
where $f_{yo}$ is the static yield strength. If the strength increase in the beams is similar to that in the tensile tests, the dynamic resistance function must be estimated from the static resistance function. It is assumed that the beam yields at a deflection of approximately 0.17 inches. Using the strain rate at that instant, the ratio $f_y/f_{yo}$ is computed from expression (A.8). All subsequent ordinates of the static load-deflection curve are then increased by this ratio. The procedure implies that subsequent changes in strain rate do not affect the resistance function.

The only difference between dynamic analysis with and without strain rate effects is that the resistance $R$ corresponding to a particular deflection $Y_j$ is determined from a different diagram.
Appendix B

MULTI DEGREE OF FREEDOM ANALYSIS OF
A BEAM SUBJECTED TO DYNAMIC THIRD POINT LOADS AND STRAIN RATE EFFECTS

B.1 The Method of Solution

The actual beam and its behavior are continuous in space and in time. In this analysis, it will be assumed that the actual beam may be replaced by the discrete model shown in Figure B.1 and that the variation of the response with time can be determined by a numerical integration technique considering discrete time intervals $dt$.

The beam is assumed to consist of rigid massless panels of length $H$, connected by flexible joints. The mass of the beam within an interval of $H/2$ on either side of the joint is lumped at the joint. Since the beam is loaded at the third points, it is found convenient to make the number of panels, $k$, a multiple of 6. There is thus always a joint at the third point and midspan. Due to symmetry, only one half of the beam needs to be considered in the analysis, which proceeds as follows:

Step 1: Propagation Formula for Displacements

Suppose that at time $t_j$, the displacements $Y_{ij}$ and accelerations $A_{ij}$ at all joints $i$ are known. Then the deflections at time $t_{j+1}$ may be computed by means of the propagation formula (8)

$$Y_{i,j+1} = 2Y_{i,j} - Y_{i,j-1} + A_{ij}(dt)^2 \quad (B.1)$$

where

$$t_{j+1} = t_j + dt$$

Step 2: Computation of the Bending Moment at Joint $i$

Once the deflections at time $t_j$ have been computed by means of equation (B.1), the curvature $R_i$ at joint $i$ may be computed from the
finite difference expression

\[ R_{i,j} = \frac{1}{H^2} (Y_{i+1,j} - 2Y_{i,j} + Y_{i-1,j}) \quad (B.2) \]

It will be assumed that the strain varies linearly over the depth of the cross-section. The cross-section is divided into a number of blocks, as shown in Figure B.1. The number of blocks in the web and in the flange are introduced as variables in the computer program. The strain at the center of each block is readily computed as the product of \( R_{i,j} \) and the distance from the neutral axis to the midpoint of the block. The stress at this point is determined from the dynamic stress-strain curve discussed in Chapter 3. The yield stress in a particular block is dependent upon the strain rate existing at the time when the yield strain is reached in that block. It is assumed that subsequent changes in the strain rate do not affect the yield stress in that particular block, as long as loading continues. Unloading is assumed to occur on a line parallel to the elastic portion of the stress-strain curve. If reloading occurs, a new yield stress is determined in accordance with a new strain rate. Once the stresses in all blocks are known, the bending moment corresponding to the curvature existing at joint \( i \) at time \( t_j \) is readily obtained through summation of the force in each block, multiplied by its moment arm.

**Step 3: Computation of the Acceleration at Joint \( i \)**

It is readily shown that the moment equilibrium of an infinitesimal element of the continuous beam, as shown in Figure B.1 is satisfied if

\[ \frac{d^2 M}{dx^2} = mA - P \]

where \( m \) is the mass per unit length of the beam, and \( A \) the acceleration. In the discrete system, the derivative of \( M \) must be replaced by a finite difference expression in terms of the value of \( M \) at the joints \( i \)

\[ \frac{d^2 M_i}{dx^2} = \frac{M_{i+1} - 2M_i + M_{i-1}}{H^2} = m_i A_i - P_i \quad (B.3) \]
JOINT WITH FLEXIBLE MASS

THIRD POINT

RIGID MASS -
LESS PANEL

L = KH

(a)

FORCE EQUILIBRIUM: \( P - M \ddot{y} = -\frac{ds}{dx} \)

(b)

FIGURE B.1
MODEL OF CONTINUOUS BEAM
where $m_i$ is the mass concentrated at joint $i$, $A_i$ the acceleration and $P_i$ the load at joint $i$. $P_i$ is zero except at the third points. In addition, a mass equal to half the mass of the loading beam is concentrated at the third points. Expression (B.3) is used to determine the acceleration $A_i$.

At time $t_j$, the displacement $Y$ of every joint is computed as outlined in step 1. Then the bending moment at all joints is computed as outlined in Step 2. Once the acceleration $A_i$ has been computed at all joints, as described in Step 3, the deflections at time $t_{j+1}$ can be computed as in Step 1. The cycle is repeated as often as desired. To maintain a reasonable accuracy in the computations, a time interval $dt$ equal to approximately one fifth of the k-th natural period of the beam is used.

Starting Procedure

Before the method of integration of Step 1 can be employed, the displacements and accelerations at the end of the first time increment must be known. The following approximate procedure is applied:

a) The beam is regarded as a one-degree elastic system, and the corresponding acceleration of the third point is computed as

$$A_{L,1} = \frac{2P}{(0.6M_i + 0.52M_{lb})}$$

where $M_{lb}$ is the mass of the loading beam and $P$ the load applied at a third point. Since the beam loads start at zero, the deflection of the third point

$$Y_{i,1} = \frac{1}{6} A_{i,1} (dt)^2 \quad (B.4)$$

The deflection and acceleration at all other points are taken as zero.

b) From the deflections computed by means of expression (B.4), the curvatures $R_{ij}$, bending moments $M_{ij}$ and acceleration $A_{ij}$ are computed as outlined above.

c) If at any joint the acceleration computed in Step b) differs by more than 5% from that computed in Step a), a new deflection curve
is determined from the accelerations computed in Step b). The iteration is continued until the change in the acceleration is less than 5% at all joints.

B.2 The Computer Program

The computer program consists of a main program with one subprogram. The subprogram determines the bending moments. The main program may be considered to be composed of three parts. The first part reads in two types of data and calculates several constants to be used later in the program. One type of data describes the geometry of the beam, the material properties, and the data from which the program calculates the load at time $t_j$. The other type of data depends on the accuracy desired and consists of the number of joints and stress blocks to be used and the size of the time increment for the numerical integration. The size of the time increment is very important since, if it is taken too large, the numerical integration will not converge. When using 12 panels, a time interval of 0.00001 second is found to be suitable. The number of panels and stress blocks should be chosen carefully, since they greatly affect the time required for execution of the program.

The second part of the main program consists of the iteration procedure which determines the deflections and accelerations at the end of the first time increment. The final part carries out the numerical integration using the results of the iteration procedure as a starting point. Figures B.2 and B.3 present flow diagrams for the main and subprograms. The Appendix is concluded by a list of the variables used in the program.
INPUT
GEOMETRY OF BEAM, MATERIAL PROPERTIES, DATA FOR THE LOAD-TIME CURVE, NUMBER OF JOINTS, STRESS BLOCKS, AND TIME INTERVALS, LENGTH OF TIME INTERVAL

PRINT ALL INPUT

CALCULATE CONSTANTS FOR LATER USE

INITIALIZE ALL DEFLECTIONS, BENDING MOMENTS AND ACCELERATIONS AT 0

APPROXIMATE DEFLECTION AND ACCELERATION FOR THIRD POINT AT END OF FIRST TIME INTERVAL USING AN EQUIVALENT ONE DEGREE SYSTEM - ALL OTHER DEFL AND ACC, ASSUMED = 0

COMPUTE CHANGE IN CURVATURE, OUTER FIBER STRAIN AND BENDING MOMENT AT ALL JOINTS

CALCULATE ACCELERATION AT ALL JOINTS AT THE END OF THE FIRST TIME INTERVAL

USING THE NEW VALUES FOR ACCELERATION COMPUTE DEFLECTION AT ALL JOINTS

YES

DOES THE ACCELERATION AT ANY JOINT DIFFER FROM THE VALUE USED AT THE BEGINNING OF THE CYCLE BY MORE THAN 5 PERCENT?

NO

COMPUTE DEFLECTION AT TIME INCREMENTED BY DT AT ALL JOINTS

COMPUTE CHANGE IN CURVATURE, OUTER FIBER STRAIN AND BENDING MOMENT AT ALL JOINTS

COMPUTE ACCELERATION AT ALL JOINTS

PRINT DESIRED OUTPUT

NO

HAS MAX TIME BEEN REACHED

YES END

FIGURE B.2
FLOW CHART FOR MAIN PROGRAM
SUBPROGRAM - DETERMINES BENDING MOMENT

IS JOINT IN ELASTIC RANGE OF STRESS-STRAIN CURVE?  YES

NO

CALCULATE STRAIN AND STRAIN RATE FOR EACH STRESS BLOCK

DETERMINE STRESS-STRAIN CURVE FOR EACH STRESS BLOCK

DO 41 K = 1, NBT (NBT = TOTAL NUMBER OF STRESS BLOCKS CONSIDERED)

CALCULATE STRESS

ASSUMING UNLOADING OCCURS ALONG THE ELASTIC CURVE

YES

NO

YES

STRESS BLOCK K PREVIOUSLY PLASTIC?

NO

IS IT NOW PLASTIC?

STOP

DOES UNLOADING OCCUR?

YES

STRESS BLOCK K PREVIOUSLY PLASTIC?

NO

RELOADING OCCURS

CALCULATE STRESS ASSUMING

RELOADING TAKES PLACE

ALONG THE ELASTIC CURVE

YES

IS YIELD STRESS EXCEEDED?

NO

ASSIGN A PERMANENT

STRESS-STRAIN CURVE

TO STRESS BLOCK K

IS THE STRAIN IN THE STRAIN HARDENING REGION?

YES

CALCULATE STRESS

IS THE STRAIN IN THE STRAIN HARDENING REGION?

NO

STRESS = YIELD STRESS

CALCULATE STRESS IN

BLOCKS K THROUGH NBT

(ALL ELASTIC)

STRESS = STRAIN X ELASTIC MODULUS

41 CONTINUE

RETURN TO MAIN PROGRAM

COMPUTE BENDING MOMENT

USING THE STRESS CALCULATED

FOR EACH BLOCK

SECTION IS COMPLETELY

ELASTIC - BENDING MOMENT =

CONSTANT x OUTER FIBER STRAIN

FIGURE B.3
FLOW CHART FOR SUBPROGRAM
LISTING OF THE PROGRAM

C DIMENSION ST(IMAX,2), BM(IMAX), STYB(IMAX,NBT), STSHB(IMAX,NBT)
C DIMENSION C(NBT), AY(NBT), STB(NBT), SB(IMAX,NBT)
C DIMENSION STR(NBT), STRY(NBT), STRSH(NBT)

DIMENSION ST(7,2), BM(7), STYB(7,4), STSHB(7,4)
DIMENSION C(4), AY(4), STB(4), SB(7,4)
DIMENSION STR(4), STRY(4), STRSH(4)

COMMON ST, NBT, C, AY, BM, DB, SGMYO, STYO, STSHO, STYB, EE, ESTH, Z, U, DT

C COMPUTATION OF STRAIN AT CENTER LINE OF EACH BLOCK

IF(STYB(I,1))7,5,7
5 IF(ST(I,2)-STYO)99,7,7
7 SGMDY=SGMYO
STYB(I,K)=STYO
STRSH(I,K)=STSHO
DO 10 K=1,NBT
10 STB(K)=ST(I,2)*C(K)/DB
DO 41 K=1,NBT
N=K
IF(STYB(I,K))26,21,26
21 IF(STB(K)-STRY(K))100,22,22
22 STYB(I,K)=STRY(K)
STSHB(I,K)=STRSH(K)
23 IF(STB(K)-STRSH(K))24,24,25
24 SB(I,K)=STYB(I,K)*EE
GO TO 41
25 SB(I,K)=STYB(I,K)*EE+(STB(K)-STRSH(K))*ESTH
GO TO 41
26 IF(ST(I,2)-ST(I,1))27,28,28
C UNLOADING TAKES PLACE ALONG ELASTIC CURVE
27 SB(I,K)+(ST(I,2)-ST(I,1))*EE*C(K)/DB
STYB(I,K)=-5.0
GO TO 41
C NO UNLOADING - WAS THERE PREVIOUS UNLOADING
28 IF(STYB(I,K))29,21,23
C PRIOR UNLOADING - NOW RELOADING
29 SB(I,K)=SB(I,K)+(ST(I,2)-ST(I,L))*EE*C(K)/DB
      IF(SB(I,K)-STRY(K)*EE)41,22,22
41 CONTINUE
      GO TO 102
C JOINT COMPLETELY ELASTIC
99 BM(I)=.0728*EE*ST(I,2)
      GO TO 104
C CALCULATION OF STRESS BLOCKS IN ELASTIC RANGE
100 DO 101 K=N,NBT
101 SB(I,K)=STB(K)*EE
C CALCULATION OF MOMENT
102 BM(I)=0.0
      DO 103 K=1,NBT
103 BM(I)=BM(I)+SB(I,K)*AY(K)
104 RETURN
END
C MAIN PROGRAM BEGINS
C DIMENSION Y(IMAX,3),A(IMAX),BM(IMAX),ST(IMAX,2),STYB(IMAX,NBT)
C DIMENSION C(NBT),AB(IMAX)
      DIMENSION Y(7,3),A(7),BM(7),ST(7,2),STYB(7,4)
      DIMENSION C(4),AY(4),AB(7)
      COMMON ST,NBT,C,AY,BM,DB,SGMYO,STYO,STSHO,STYB,EE,ESTH,Z,U,DT
501 FORMAT(3I5,F10.7)
502 FORMAT(14H NO. TIME INC.,I5,5H EACH,F10.7,4H SEC)
503 FORMAT(1H,3I5)
5031 FORMAT(5F10.4)
5032 FORMAT(iH,5F10.4)
504 FORMAT(11H NO. PANELS,I5,14H BLOCKS FLANGE,I5,11H BLOCKS WEB,I5)
506 FORMAT(40H NOT VALID ADJUST NP TO BE MULTIPLE OF 6)
507 FORMAT(5F10.4,F11.8)
FORMAT(2F10.6,2F10.0)
FORMAT(F10.0,F10.7,F10.4)
FORMAT(2H Y,E18.8,2H A,E18.8,3H BM,E18.8,1H J1,1H J2,1H J3,15)
FORMAT(5H LOAD,F10.4,8H REACTION,F10.4,4HTIME,F10.7,3H SEC)
FORMAT(1H,5F10.4,F11.8)
FORMAT(1H,2F10.6,2F10.0)
FORMAT(1H,F10.0,F10.7,F10.4)
FORMAT(23H PRINT DATA ONCE EVERY ,I4,11H INCREMENTS)
READ 501,J1,J2,J3,DT
PRINT 502,J3,DT
PRINT 503,J1,J2
EJ1=J1
EJ2=J2
READ 5031,G1,G2,PO,PMAX
PRINT 5032,G1,G2,PO,PMAX
READ 501,JTIN
PRINT 538,JTIN
C READ IN NO. OF PANELS AND STRESS BLOCKS TO BE CONSIDERED
C NP(NUMBER OF PANELS) MUST BE A MULTIPLE OF 6
READ 504,NP,NBF,NBW
NBT=NBF +NBW
PRINT 505,NP,NBF,NBW
IF(NP/6*6-NP)2,3,2
2 PRINT 506
CALL EXIT
C READ IN GEOMETRY OF BEAM
3 READ 507,B,D,W,T,SPAN,AMLI
PRINT 523,B,D,W,T,SPAN,AMLI
DB=D+T
C READ IN MATERIAL PROPERTIES
READ 508,STYO,STSHO,EE,ESTH
PRINT 524,STYO,STSHO,EE,ESTH
READ 509,SGMYO,U,Z.
PRINT 525,SGMYO,U,Z
CALCULATION OF KEY JOINT NUMBERS

IMAX=NP/2 +L
IE=IMAX-1
L=NP/3 +1
SK=NP
H=SPAN/SK
AMASS=H*AMLI

INITIALIZATION OF VARIABLES

DO 10 I=1,IMAX
A(I)=0.0
ST(I,1)=0.0
BM(I)=0.0
DO 9 J=1,3
9 Y(I,J)=0.0
DO 10 K=1,NBT
10 STYB(I,K)=0.0

DETERMINATION OF CONSTANTS FOR MOMENT CALCULATION

Q1=NBF
Q2=NBW
DO 11 I=1,NBF
Q4=2*(NBF-I)+1
C(I)=D+T*Q4/Q1/2.
11 AY(I)=B*T/Q1*C(I)*2.
DO 12 I=1,NBW
K=NBF+I
Q4=2*(NBW-I)+L
C(K)=D*Q4/Q2/2.
12 AY(K)=W*D*C(K)*2./Q2

ESTIMATE ACCELERATION AT THIRD POINT BY EQUIVALENT 1 DEGREE SYSTEM

A(L)=2.*P0/(0.6*SPAN*AMLI+0.52*.000804)
Y(L,2)=A(L)*DT**2/6.

DO 21 I=2,IMAX
IF(I-IMAX)18,19,18
18 \[ R = \frac{Y(I+1,2) - 2 \cdot Y(I,2) + Y(I-1,2)}{H^2} \]
GO TO 20
19 \[ R = \frac{2 \cdot (Y(I-1,2) - Y(I,2))}{H^2} \]
20 \[ ST(I,2) = -R \cdot DB \]
CALL MOMNT(I)
21 CONTINUE
DO 24 I=2,IE
IF(I-L)23,22,23
22 \[ AB(I) = \frac{(Po + (BM(I+1) - 2 \cdot BM(I) + BM(I-1))/H)}{(AMASS + 0.000804)} \]
GO TO 24
23 \[ AB(I) = \frac{(BM(I+1) - 2 \cdot BM(I) + BM(I-1))}{H/AMASS} \]
24 CONTINUE
\[ AB(IMAX) = \frac{2 \cdot (BM(IMAX-1) - BM(IMAX))}{H/AMASS} \]
DO 25 I=2,IMAX
IF(ABS((AB(I)-A(I))/AB(I)*100.) - 5.)25,25,26
25 CONTINUE
GO TO 30
26 DO 27 I=2,IMAX
A(I) = AB(I)
27 \[ Y(I,2) = A(I) \cdot DT^2/6 \]
GO TO 16
C A AND Y NOW KNOWN AT ALL POINTS AT TIME DT OR J=2
C PROCEEDING WITH NUMERICAL INTEGRATION
30 DO 28 I=2,IMAX
28 \[ ST(I,1) = ST(I,2) \]
DO 100 J=3,J3
C COMPUTE LOAD
IR=J-1
IF(IR-J1)31,31,32
31 \[ P = EJ \cdot G1 \]
GO TO 40
32 IF(IR-J2)33,33,36
33 \[ P = EJ1 \cdot G1 + (EJ-EJ1) \cdot G2 \]
GO TO 40
36 P=PMAX
C COMPUTATION OF DEFLECTION AT TIME INCREMENTED BY DT
40 DO 50 I=2,IMAX
50 Y(I,3)=2.*Y(I,2)-Y(I,1)+A(I)*DT**2
C COMPUTATION OF STRAIN
DO 60 I=2,IE
R=(Y(I+1,3)-2.*Y(I,3)+Y(I-1,3))/H**2
ST(I,2)=-R*DB
CALL MOMNT(I)
60 CONTINUE
R=2.*(Y(IMAX-1,3)-Y(IMAX,3))/H**2
ST(IMAX,2)=-R*DB
CALL MOMNT(IMAX)
C COMPUTATION OF ACCELERATION
DO 79 I=2,IE
C JOINT AT THIRD POINT CONSIDERED SEPARATELY DUE TO LOAD
IF(I-L)72,71,72
71 A(I)=(P+(BM(I+1)-2.*BM(I)+BM(I-1))/H)/(AMASS+.000804)
GO TO 79
72 A(I)=(BM(I+1)-2.*BM(I)+BM(I-1))/H/AMASS
79 CONTINUE
A(IMAX)=2.*(BM(IMAX-1)-BM(IMAX))/H/AMASS
IF((J-1)/JTIN*JTIN-(J-1))81,82,81
81 GO TO 91
C COMPUTATION OF END REACTION
82 SUMA=0.0
DO 85 I=2,IE
85 SUMA=SUMA+A(I)
SUMA=SUMA+A(IMAX)/2.
REND=P-SUMA*AMASS
Q3=J-1
TIME=Q3*DT
PRINT 522,P,REND,TIME

90 PRINT 510,Y(IMAX,3),A(IMAX),BM(IMAX),IMAX,J

91 DO 100 I=2,IMAX
   Y(I,1)+Y(I,2)
   Y(I,2)=Y(I,3)

100 ST(I,1)=ST(I,2)
    CALL EXIT
    END
NOTATION USED ON COMPUTER PROGRAM FOR BEAM ANALYSIS

DT – TIME INCREMENT
P – THIRD POINT LOAD
K – NUMBER OF PANELS CONSIDERED
H – PANEL LENGTH
IMAX – JOINT NUMBER AT CENTER LINE
L – JOINT NUMBER AT THIRD POINT
NBF – NUMBER OF STRESS BLOCKS CONSIDERED IN FLANGE
NBW – NUMBER OF STRESS BLOCKS CONSIDERED IN WEB
NBT – TOTAL NUMBER OF STRESS BLOCKS CONSIDERED
SPAN – BEAM LENGTH
AMLI – MASS PER LINEAR INCH OF BEAM
AMASS – MASS AT EACH JOINT
B – WIDTH OF FLANGE
D – HALF DEPTH OF WEB
Db – HALF DEPTH OF BEAM
W – THICKNESS OF WEB
T – THICKNESS OF FLANGE
STYO – STATIC YIELD STRAIN
STSHO – STATIC STRAIN HARDENING STRAIN
EE – MODULUS OF ELASTICITY – ELASTIC RANGE
ESTH – MODULUS OF ELASTICITY – STRAIN HARDENING RANGE
SGMYO – STATIC YIELD STRESS
SGMDY – DYNAMIC YIELD STRESS
U – STRAIN RATE (MAX) AT WHICH SGMDY = SGMYO
Z – SLOPE OF LOG (STRAIN RATE) VS SGMDY
ST (I,2) – OUTER FIBERSTRAIN JOINT I, TIME J
Y (I,3) – DEFLECTION JOINT I, TIME J
A(I) – ACCELERATION JOINT I
BM (I) – BENDING MOMENT JOINT I
REND – END REACTION
STYB (I,K) – YIELD STRAIN ASSIGNED JOINT I, BLOCK K
STSHB (I, K) - STR. HARD. STRAIN ASSIGNED JOINT I, BLOCK K
SB (I, K) - STRESS, JOINT I, AT CENTER OF BLOCK K
STB (K) - STRAIN, BLOCK K
C (K) - DISTANCE FROM CENTER LINE OF BEAM TO C.L. BLOCK K
AY (K) - AREA BLOCK K MULTIPLIED BY 2 C (K)
R - CHANGE IN CURVATURE
OFSTR - STRAIN RATE AT THE OUTER FIBER
STR (K) - STRAIN RATE AT CENTER OF BLOCK K
STRY (K) - YIELD STRAIN ASSOC. WITH THE CURRENT STRAIN RATE IN BLOCK K
STRSH (K) - STRAIN HARDENING STRAIN ASSOC. WITH THE CURRENT STRAIN RATE IN BLOCK K
J1, J2, J3, G1, G2, G3 - CONSTANTS ASSOC. WITH LOAD-TIME CURVE
PO - LOAD AT J = 2
PMAX - VALUE WHEN LOAD IS CONST.
C.1 Idealized Static Analysis

The actual geometry of the portal frames that have been tested is indicated in Figure 5.1. If it is assumed that the real structure may be represented by an idealized system whose dimensions equal the centerline dimensions of the real structure, and which is assumed to be rigidly supported at the base and rigidly jointed at the knee, it is readily shown \(^{(10)}\) that in the elastic range

\[
M_A = -\frac{Ph}{2} \frac{3k + 1}{6k + 1}
\]

\[
M_B = \frac{Ph}{2} \frac{3k}{6k + 1}
\]

where

\[
k = \frac{h}{L} \frac{I_1}{I_2}
\]

and

\[
h = \text{height of frame}
\]

\[
L = \text{span of frame}
\]

\[
I_1 = \text{moment of inertia of column}
\]

\[
I_2 = \text{moment of inertia of girder}
\]

The deflection \(Y\) in the horizontal direction, as indicated in Figure C.1, may be computed from the moment-area theorem

\[
Y = \frac{Ph^3}{12EI_1} \frac{3k + 2}{6k + 1} \quad (C.1)
\]

The following constants are used in the computations which have been summarized in Table C.1:
PROPERTIES OF FRAME

COLLAPSE MECHANISM

FIGURE C.1
IDEALIZATION OF FRAME
h = 12.2 inches \quad L = 16.0 \text{ inches}

8 WF 31: \quad I = 0.0118 \text{ inch}^4
8 WF 67: \quad I = 0.0278 \text{ inch}^4
E = 27.9 \times 10^6 \text{ psi}

The first plastic hinge forms when either $M_A$ or $M_B$ reaches the moment capacity of the section, which is assumed to be given by:

$$M_p = 1.05 \frac{I \sigma_y}{0.5d}$$

when

- $I$ = moment of inertia
- $d$ = depth between midheight of flanges
- $\sigma_y$ = 62,000 psi

so that

- $M_p = 1910 \text{ lb inch for 8 WF 31 model}$
- $M_p = 4000 \text{ lb inch for 8 WF 67 model}$

In frames I to III, the first hinge forms at the base, while in frame IV, the first hinge forms at the knee. The plastic analysis for the two cases, which is carried out by the method suggested by Beedle (9), differs.

**First hinge forms at base:**

The load causing the first hinge to form is given by

$$P_1 = \frac{2M_{pA}}{h} \frac{6k + 1}{3k + 1} \quad \text{(C.2)}$$

The corresponding lateral deflection $Y_1$ may be computed from equation (C.1). If the load is increased further, a second hinge forms at the knee, and a collapse mechanism is formed as shown in Figure C.1. The load $P_2$ at which the second hinge forms is given by

$$P_2 = \frac{2}{h} (M_{pA} + M_{pB}) \quad \text{(C.3)}$$

The corresponding deflection $Y_2$ is found by means of the moment area theorem, setting $\theta_{BA} = \theta_{BC}$:

$$Y_2 = \frac{h}{6E} \left[ \frac{h}{I_1} (2M_{PB} - M_{pA}) + \frac{L}{I_2} M_{pB} \right] \quad \text{(C.4)}$$

105
All computations are summarized in Table C.1.

**First hinge forms at knee:**

The load causing the first hinge to form is given by

\[
P_1 = \frac{2M_B}{h} \frac{6k + 1}{3k}
\]  

(C.5)

The lateral deflection \( Y_1 \) is computed by means of equation (C.1). The load \( P_2 \) leading to collapse of the structure is again given by equation (C.3). The corresponding deflection \( Y_2 \) is found by means of the moment area theorem, setting \( \theta_{AB} = 0 \):

\[
Y_2 = \frac{h^2}{6EI_1} (2M_A - M_B)
\]  

(C.6)

### Table C.1: Static Response of Idealized Frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>( I_1 )</th>
<th>( I_2 )</th>
<th>( k )</th>
<th>( M_A )</th>
<th>( M_B )</th>
<th>( P_1 )</th>
<th>( Y_1 )</th>
<th>( P_2 )</th>
<th>( Y_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.0278</td>
<td>0.0278</td>
<td>0.761</td>
<td>4000</td>
<td>4000</td>
<td>1120</td>
<td>0.167</td>
<td>1320</td>
<td>0.298</td>
</tr>
<tr>
<td>II</td>
<td>0.0118</td>
<td>0.0118</td>
<td>0.761</td>
<td>1910</td>
<td>1910</td>
<td>530</td>
<td>0.188</td>
<td>640</td>
<td>0.335</td>
</tr>
<tr>
<td>III</td>
<td>0.0118</td>
<td>0.0278</td>
<td>1.80</td>
<td>1910</td>
<td>4000</td>
<td>580</td>
<td>0.165</td>
<td>640</td>
<td>0.225</td>
</tr>
<tr>
<td>IV</td>
<td>0.0278</td>
<td>0.0118</td>
<td>0.324</td>
<td>4000</td>
<td>1910</td>
<td>940</td>
<td>0.189</td>
<td>970</td>
<td>0.194</td>
</tr>
</tbody>
</table>

### C.2 Effect of Knee Flexibility and Base Flexibility

In the actual model frames, neither the knee nor the base is completely rigid. An exact analysis accounting for these parameters can be performed, as illustrated in reference (11). Within the scope of the present report, it is considered sufficient to perform the following approximate analysis, which is shown to lead to predictions that are in good agreement with the experimental observations.

According to the Welding Research Council (12), the rotation in a square symmetric knee may be determined from the expression

\[
\theta = F_{avg} \left[ \frac{k_3}{d} + \frac{1 + k_2}{A_f dE} \right]
\]  

(C.7)
where

\[
    k_2 = \left[1 + \frac{1.41}{1 + 2\nu} \frac{A_w}{A_s}\right]^{-1}
\]

\[
    k_3 = \left[\frac{Et_w}{2(1 + \nu)} + \frac{A_sE}{2.82}\right]^{-1}
\]

and

\[
    F_{\text{ave}} = \text{average force in flanges}
\]

\[
d = \text{center to center distance between flanges}
\]

\[
    A_f = \text{area of one flange}
\]

\[
    A_w = \text{area of web in shear}
\]

\[
    A_s = \text{area of 45° stiffener}
\]

\[
t_w = \text{thickness of web}
\]

\[
    E = \text{modulus of elasticity}
\]

\[
    \nu = \text{Poisson's Ratio}
\]

The knees of the four frame types are not completely square and symmetric. It is decided to use average values of constants such as \(d\), \(A_f\), etc. as indicated in Table C.2, which also contains the values of the rotation \(\theta\). The average force \(F_{\text{avg}}\) is determined by dividing \(M_B\) through the depth \(d\). Two different values of \(\theta_1\) are obtained, one corresponding to the formation of the first hinge, the other to the formation of the second hinge.

The analysis of the idealized structure, as performed in Section C.1, accounts for a portion \(\theta_2\) of the rotation \(\theta\) computed above. It is given approximately by

\[
    \theta_2 = \frac{Md}{EI} \quad (C.8)
\]

where, again, average values should be used for \(d\) and \(I\). The rotation that is not accounted for by the idealized analysis is therefore

\[
    \theta = \theta_1 - \theta_2
\]

It is computed in Table C.2, using \(E = 27.9 \times 10^6 \text{ psi}\) and \(\nu = 0.3\).
Table C.2: Effect of Knee Flexibility

<table>
<thead>
<tr>
<th>Frame</th>
<th>d</th>
<th>A_f</th>
<th>t_w</th>
<th>A_v</th>
<th>A_s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inch</td>
<td>in²</td>
<td>inch</td>
<td>in²</td>
<td>in²</td>
</tr>
<tr>
<td>I</td>
<td>0.807</td>
<td>0.0815</td>
<td>0.058</td>
<td>0.0410</td>
<td>0.080</td>
</tr>
<tr>
<td>II</td>
<td>0.760</td>
<td>0.0384</td>
<td>0.028</td>
<td>0.0200</td>
<td>0.080</td>
</tr>
<tr>
<td>III</td>
<td>0.783</td>
<td>0.0600</td>
<td>0.043</td>
<td>0.0305</td>
<td>0.080</td>
</tr>
<tr>
<td>IV</td>
<td>0.783</td>
<td>0.0600</td>
<td>0.043</td>
<td>0.0305</td>
<td>0.080</td>
</tr>
</tbody>
</table>

1.Hinge

<table>
<thead>
<tr>
<th>Frame</th>
<th>F_avg</th>
<th>lb</th>
<th>k_2</th>
<th>k_3E</th>
<th>θ_1</th>
<th>θ_2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10^-3 rad</td>
<td>10^-3 rad</td>
<td>10^-3 rad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>3470</td>
<td>0.644</td>
<td>21.5</td>
<td>6.41</td>
<td>2.93</td>
<td>3.48</td>
</tr>
<tr>
<td>II</td>
<td>1950</td>
<td>0.786</td>
<td>27.3</td>
<td>6.79</td>
<td>3.40</td>
<td>3.39</td>
</tr>
<tr>
<td>III</td>
<td>2070</td>
<td>0.709</td>
<td>24.1</td>
<td>5.00</td>
<td>2.30</td>
<td>2.70</td>
</tr>
<tr>
<td>IV</td>
<td>2440</td>
<td>0.709</td>
<td>24.1</td>
<td>5.88</td>
<td>2.72</td>
<td>3.16</td>
</tr>
</tbody>
</table>

2.Hinge

<table>
<thead>
<tr>
<th>Frame</th>
<th>F_avg</th>
<th>lb</th>
<th>k_2</th>
<th>k_3E</th>
<th>θ_1</th>
<th>θ_2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10^-3 rad</td>
<td>10^-3 rad</td>
<td>10^-3 rad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>4960</td>
<td>0.644</td>
<td>21.5</td>
<td>9.15</td>
<td>4.20</td>
<td>4.95</td>
</tr>
<tr>
<td>II</td>
<td>2510</td>
<td>0.786</td>
<td>27.3</td>
<td>8.80</td>
<td>4.40</td>
<td>4.40</td>
</tr>
<tr>
<td>III</td>
<td>2440</td>
<td>0.709</td>
<td>24.1</td>
<td>5.90</td>
<td>2.71</td>
<td>3.19</td>
</tr>
<tr>
<td>IV</td>
<td>2440</td>
<td>0.709</td>
<td>24.1</td>
<td>5.88</td>
<td>2.72</td>
<td>3.16</td>
</tr>
</tbody>
</table>

The effect of the additional rotation θ on the displacement Y in a rigorous analysis should be determined through redistribution of the moments. In view of the uncertainty of base flexibility, a different procedure is followed here, as shown below.

The bases of the frames have been fixed as carefully as was technologically possible. It is known from large scale tests(11) that even an apparently suitable base connection can have sufficient rotation flexibility to increase the effective length of the columns by 25%
(see p. 55 in reference (11) where different flexibility coefficients are discussed). In the present investigation, it will be assumed that the base flexibility has the following effects:

i) It permits the additional deflection $Y_k$ due to a combination of knee and base flexibility to be computed as

$$Y_k = \theta h$$  \hspace{1cm} (C.9)

where $\theta$ is given in Table C.2.

ii) The effective length of the column is increased by a percentage $P$ which has to be estimated. Generally, the model column bases are assumed to be more rigidly fixed than those in the large scale tests (11). The percentage increase in the four frames will be different in view of the different $I_1/I_2$ ratios and the different column stiffness as governed by the value of $I_1$. The estimates are given in Table C.3. It is seen from equations (C.1) and (C.2) that the deflections $Y_1$ and $Y_2$ are essentially proportional to the square of the column height $h$. The corrected deflections will therefore be computed as

$$Y_c = \left[ \frac{h_c}{h} \right]^2 Y$$  \hspace{1cm} (C.10)

where $h_c$ is the new effective column length and $Y$ is taken from Table C.1. The final deflections of the frame are then given by

$$Y_f = Y_k + Y_c$$  \hspace{1cm} (C.11)

All computations are summarized in Table C.3.
Table C.3: Static Response of Actual Frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>( P )</th>
<th>( \left[ \frac{h_c}{h} \right]^2 )</th>
<th>( Y_{1c} )</th>
<th>( Y_{2c} )</th>
<th>( Y_{1k} )</th>
<th>( Y_{2k} )</th>
<th>( Y_{1f} )</th>
<th>( Y_{2f} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>8</td>
<td>1.16</td>
<td>0.193</td>
<td>0.345</td>
<td>0.043</td>
<td>0.061</td>
<td>0.236</td>
<td>0.406</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td>1.06</td>
<td>0.200</td>
<td>0.355</td>
<td>0.042</td>
<td>0.054</td>
<td>0.242</td>
<td>0.409</td>
</tr>
<tr>
<td>III</td>
<td>5</td>
<td>1.10</td>
<td>0.182</td>
<td>0.246</td>
<td>0.033</td>
<td>0.039</td>
<td>0.215</td>
<td>0.285</td>
</tr>
<tr>
<td>IV</td>
<td>25</td>
<td>1.56</td>
<td>0.295</td>
<td>0.302</td>
<td>0.038</td>
<td>0.038</td>
<td>0.333</td>
<td>0.340</td>
</tr>
</tbody>
</table>

C.3 Dynamic Analysis

The dynamic analysis of the frame structures is performed by means of an equivalent one degree of freedom system, as shown in Figure C.2. This approximation, which has been shown to be suitable for the beam tests in Chapter 4, is expected to be even more applicable to the frames when a large portion of the mass, i.e. the girder, lies along the line of action of the applied force. The properties of the equivalent system are determined as follows:

i) The equivalent mass \( M_e \) equals the mass of the girder, the mass of the load cell plus its bearing plate, and one half of the total mass of the two columns.

ii) The applied load and the resistance of the one degree of freedom system equal those of the actual frame.

Two methods of solution have been investigated. Initially, a series of theoretical solutions were obtained by means of the computer program described in section C.4. The program is used with a bilinear load function, as shown in Figure C.2. The bilinear resistance function can either be specified as input, or it can be computed internally from the member properties as described in section C.1. The program does not yield reasonable predictions of the experimentally observed behavior.

A second series of solutions has been performed, using the actual load function and the static resistance function of the frames.
**FIGURE C.2**
Idealization of Frame Structure
The predictions, and the correlation with experimental observations, are discussed in Chapter 5. The method of integration is the same as that discussed in appendix A for the one degree system representing the beams.

Table C.4: Properties of Equivalent Dynamic System

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of beam</td>
<td>lb</td>
<td>1.14</td>
<td>0.60</td>
<td>1.14</td>
<td>0.60</td>
</tr>
<tr>
<td>Weight of one column</td>
<td>lb</td>
<td>0.81</td>
<td>0.51</td>
<td>0.51</td>
<td>0.81</td>
</tr>
<tr>
<td>Weight of load cell and bearing plate</td>
<td>lb</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Total weight</td>
<td>lb</td>
<td>2.20</td>
<td>1.36</td>
<td>1.90</td>
<td>1.66</td>
</tr>
<tr>
<td>Equivalent mass</td>
<td>lbsec²/inch</td>
<td>0.00570</td>
<td>0.00352</td>
<td>0.00493</td>
<td>0.00429</td>
</tr>
<tr>
<td>Stiffness</td>
<td>lb/inch</td>
<td>4800</td>
<td>2220</td>
<td>2550</td>
<td>2700</td>
</tr>
<tr>
<td>Period</td>
<td>millisec</td>
<td>6.84</td>
<td>7.90</td>
<td>8.73</td>
<td>8.00</td>
</tr>
</tbody>
</table>

The strain rate at the time when the first hinge forms is computed as described below. Although the tension tests predict considerable strength increases at these strain rates, the static resistance function is used in the dynamic analysis (this is optional in the computer program) because the beam tests predict essentially no increase in the resistance function, and because the predictions of the frame behavior based on this assumption show good agreement with the experimental observations.

The determination of strain rate, as in the case of the beam tests, needs to be approximate only since the logarithm of the strain rate determines the strength increase. The deflection, as determined during the numerical integration, is used to determine the bending moment at the base through use of equation (C.1) and the preceeding expression for \( M_a \):

\[
M_a = -\frac{6EIY}{h^2} \cdot \frac{3k + 1}{3k + 2}
\] (C.12)
The strain at the center of the column flange is then given by
\[ \varepsilon = \frac{M_d}{2I_h E} = -\frac{3Y_d}{h^2} \left( \frac{3k + 1}{3k + 2} \right) \]  
(C.13)

The strain rate at yielding, when \( Y = Y_{lf} \) as computed in section C.2, is readily computed as
\[ \dot{\varepsilon} = \frac{\varepsilon_j - \varepsilon_{j-1}}{dt} \]  
(C.14)

when \( \varepsilon_j \) is the strain at time \( t_j \), and \( dt \) is the time interval (1 millisecond) used in the integration procedure. The corresponding tensile strength increase is given by equation (A.8). Typical values are quoted in Chapter 5.

C.4 Computer Program

The flow chart of the computer program is presented in Figure C.3. A listing of the program completes this appendix. The following notation is used:

1) **Input Variable**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, B = 0</td>
<td>constant used to vary the strain rate-yield stress relationship denotes no strain rate effect</td>
</tr>
<tr>
<td>B = 1</td>
<td>denotes strain rate effect according to (A.8)</td>
</tr>
<tr>
<td>TYPE</td>
<td>designation for frame type I, II, III, or IV</td>
</tr>
<tr>
<td>F1, F2, RT1, RT2</td>
<td>coordinates of bi-linear load-time function</td>
</tr>
<tr>
<td>DEL</td>
<td>time increment, dt</td>
</tr>
<tr>
<td>E</td>
<td>modulus of elasticity</td>
</tr>
<tr>
<td>SIGYS</td>
<td>static yield stress</td>
</tr>
</tbody>
</table>
ii) Output Variables

X(I) = lateral deflection of the frame at time station I

ACCEL(I) = lateral acceleration at time station I

VD(I) = horizontal shear at point D of the frame at time station I

F(I) = applied load at time station I

H = frame height
S = frame span
CWT = weight per inch for the column
BWT = weight per inch for the girder
DB = girder depth
BB = girder width
TB = flange thickness of the girder
WB = web thickness of the girder
DC = column depth
BC = column width
TC = flange thickness of the column
WC = web thickness of the column
R1IN, X1IN, R2IN, X2IN = coordinates of the static resistance function
FIGURE C.3 FLOW CHART FOR FRAME ANALYSIS

FLOW CHART

Read frame geometry, frame type, material properties, load-time function, resistance function (optional), and time increment.

Print all input.

Initialize all subscripted variables and define initial conditions.

Compute values of all constants required in subsequent calculations.

Compute bending moment and bending strain at point D.

Compute strain rate and corresponding dynamic yield stress at point D.

Compute coordinates $R_1$ and $X_1$ of the resistance function.

Select the appropriate load.

Compute the frame acceleration from the equation of motion. Compute the column shear at D.

Compute $X(t + t)$ from the recurrence formula.

Increase $t$ by $\Delta t$.

YES: Is $X(t + t) \leq X_1$?

NO:

Compute bending moment and bending strain at C.

Compute strain rate and corresponding dynamic yield stress at point C.

Compute coordinates $R_2$ and $X_2$ of the resistance function.

YES: Is $X(t) < X_2$?

NO:

Compute appropriate resistance function.

Select appropriate load.

Compute frame acceleration from the equation of motion. Compute the column shear at D.

Compute $X(t + \Delta t)$.

NO: Is $X(t + \Delta t) < X(t)$?

YES:

Print TIME, $X(t)$, ACCEL($t$), VD($t$), and F($t$).

YES: Does more input data exist?

NO: STOP
LISTING OF THE PROGRAM

DIMENSION X(200), ACCEL(200), VD(200), F(200)

200 READ 101, B, TYPE
   READ 102, F1, F2, RT1, RT2, DEL
   READ 103, E, SIGYS
   READ 104, H, S, CWT, BWT
   READ 105, DB, BB, TB, WB
   READ 105, DC, BC, TC, WC
   READ 115, R1IN, X1IN, R2IN, X2IN
   PRINT 106, B, TYPE
   PRINT 107, F1, F2, RT1, RT2, DEL
   PRINT 108, E, SIGYS
   PRINT 109, H, S, CWT, BWT
   PRINT 112

101 FORMAT(2F10.2)
102 FORMAT(2F10.3, 3F10.4)
103 FORMAT(2F20.0)
104 FORMAT(2F10.4, 2F10.6)
105 FORMAT(4F10.4)
106 FORMAT(1H, 2F5.2)
107 FORMAT(1H, 2F10.3, 3F10.4)
108 FORMAT(2F20.0)
109 FORMAT(1H, 2F10.4, 2F10.6)
110 FORMAT(4H R1=, F10.2, 4H X1=, F10.6, 4H R2=, F10.2, 4H X2=, F10.6/4H T
111 FORMAT(7H SIGDD=, F10.2, 7H SIGDC=, F10.2)
112 FORMAT(19H I TIME /64H X(I) ACCEL(I)
113 FORMAT(1H, I4, F10.5/4E18.8)
114 FORMAT(12H ERROR IN 29)
FORMAT(4F10.4)
DO 10 L=1,200
X(L)=0.0
ACCEL(L)=0.0
VD(L)=0.0
F(L)=0.0
10 CONTINUE
ED=0.00000000
JJ1=100
JJ2=0
JJ3=0
BI=(BB*TB**3)/6.0+(BB*TB*(DB-TB)**2)/2.0+WB*(DB-2.0*TB)**3/12.0
BZ=BB*TB*(DB-TB)+WB*(DB-2.0*TB)**2
CI=(BC*TC**3)/6.0+(BC*TC*(DC-TC)**2)/2.0+(WC*(DC-2.0*TC)**3)/12
CZ=BC*TC*(DC-TC)+WC*(DC-2.0*TC)**2
RK=BI*H/(CI*S)
IF(RlIN-0.0)200,5,6
5
RlIN=SIGYS*CZ*(12.0*RK+2.0)/((H*(3.0*RK+1.0))
XlIN=(RlIN*H**3)*(3.0*RK+2.0)/(12.0*E*CI*(6.0*RK+1.0))
AK1=RlIN/XlIn
R2In=4.0*SIGYS*CZ/H
X2In=XlIn+(R2In-RlIN)*(H**3)*(2.0*RK+1.0)/(12.0*E*CI*RK)
AK2=(R2In-RlIN)/(X2In-XlIn)
GO TO 7
6
AK1=RlIN/XlIn
AK2=(R2In-RlIN)/(X2In-XlIn)
7
EQWT=2.0*CWT*H/3.0+BWT*S
EQMAS=EQWT/386.4
TN=2.0*3.14159*SQR(EQMAS/AK1)
X(2)=F1*(DEL**3)/(6.0*EQMAS*RT1*(1.0+AK1*DEL**2)/6.0*EQMAS))
DO 20 I=2,200
BMD=AK1*X(I)*H*(3.0*RK+1.0)/(12.0*RK+2.0)
EDO=ED
ED = BMD * (DC - TC) / (2.0 * E * CI)
EDRAT = ABS((ED - EDO) / DEL)
IF(EDRAT = 0.0) 200, 11, 12

11 SIGDD = SIGYS
GO TO 14

12 Q = 0.4329 * (ALOG(EDRAT) - ALOG(0.000028)) / 100.0
SIGDD = SIGYS * (1.0 + B * 0.4329 * 4.33 * Q)

14 RL = SIGDD * RLIN / SIGYS
X1 = RL / AK1
AI = I - 1
IF(AI * DEL = RT1) 21, 21, 22

21 F(I) = F1 * AI * DEL / RT1
GO TO 25

22 IF(AI * DEL = RT2) 23, 23, 24

23 F(I) = F1 + (F2 - F1) * (AI * DEL - RT1) / (RT2 - RT1)
GO TO 25

24 F(I) = F2

25 R = AK1 * X(I)
ACCEL(I) = (F(I) - R) / EQMAS
VD(I) = F(I) / 2.0 - (BWT*S - CWT*H/2.0) * ACCEL(I) / (2.0 * 386.4)
X(I+1) = 2.0 * X(I) - X(I-1) + ACCEL(I) * DEL**2
IF(X(I+1) - X1) 20, 29, 29
CONTINUE

29 JJ1 = I
IF(TYPE = 4.0) 41, 31, 13

13 PRINT 114
GO TO 200

31 M = I + 1
DO 30 J = M, 200
AJ = J - 1
IF(AJ * DEL = RT1) 32, 32, 33

32 F(J) = F1 * AJ * DEL / RT1
GO TO 36

118
33 IF(AJ*DEL-RT2)34,34,35
34 F(J)=F1+(F2-F1)*(AJ*DEL-RT1)/(RT2-RT1)
GO TO 36
35 F(J)=F2
36 R=R1
ACCEL(J)=(F(J)-R)/EQMAS
VD(J)=F(J)/2.0-(BWT*S-CWT*H/2.0)*ACCEL(J)/(2.0*386.4)
X(J+1)=2.0*X(J)-X(J-1)+ACCEL(J)*DEL**2
IF(X(J+1)-X(J))61,30,30
30 CONTINUE
JJ2=J
41 R2=R1+R2IN-R1IN
X2=X1+X2IN-X1IN
BMC=R1*H*3.0*RK/(12.0*RK+2.0)
EC=BMC*(DC-TC)/(2.0*E*CI)
N=I+1
DO 40 K=N,200
BMC=(R1*H*3.0*RK/(12.0*RK+2.0))+AK2*H*(X(K)-X1)/2.0
ECO=EC
EC=BMC*(DC-TC)/(2.0*E*CI)
ECRAT=ABS((EC-ECO)/DEL)
SIGDC=SIGYS*(1.0+B*0.4329*4.33*ALOG(ECRAT/0.000028)/100.0)
IF(X(K)-X2)42,42,43
42 R2=R1+(R2IN-R1IN)*SIGDC/SIGYS
X2=X1+(R2-R1)/AK2
43 AK=K-1
IF(AK*DEL-RT1)44,44,45
44 F(K)=F1*AK*DEL/RT1
GO TO 48
45 IF(AK*DEL-RT2)46,46,47
46 F(K)=F1+(F2-F1)*(AK*DEL-RT1)/(RT2-RT1)
GO TO 48
47 F(K)=F2
48 IF(X(K)-X2)49,50,50
49 R=R1+(X(K)-X1)*AK2
GO TO 51
50  R=R2
51  ACCEL(K)=(F(K)-R)/EQMAS
     VD(K)=F(K)/2.0-(BWT*S-CWT*H/2.0)*ACCEL(K)/(2.0*386.4)
     X(K+1)=2.0*X(K)-X(K-1)+ACCEL(K)*DEL**2
     IF(X(K+1)-X(K))60,40,40
40  CONTINUE
60  JJ3=K
     IF(TYPE-4.0)62,61,13
61  JJ2=J
     IMAX=JJ1+JJ2
     GO TO 99
62  JJ1=I
     IMAX=JJ1+JJ3
99  DO 100 I=1,IMAX
     AI=I-1
     TIME=AI*DEL
     PRINT 113,I,TIME,X(I),ACCEL(I),VD(I),F(I)
100  CONTINUE
     PRINT 110,R1,X1,R2,X2,TN
     PRINT 11,SIGDD,SIGDC
     GO TO 200
END
Appendix D

ADDITIONAL BEAM TESTS

The tests described in the main part of this report have been performed on models manufactured out of SAE 1113 steel. The beam and frame tests presented in chapters 4 and 5 indicate consistently that the strain rate does not affect the resistance function of the models. The tests do not indicate whether this surprising result should be attributed to the properties of the SAE 1113 steel or whether the increase in the yield strength of steel in a bending test differs significantly from that in a tensile test. It was therefore decided to perform additional beam tests, using models cut from SAE 1020 rather than SAE 1113 steel. The manufacturing and testing procedures were the same as those described in chapter 4. The results are summarized in this appendix.

The test beams are 1 in 15 scale models of 14 WF 103 prototype sections, with an overall depth of 0.96 inches, a flange width of 0.97 inches, a web thickness of 0.032 inches and flange thicknesses of 0.055 inches. The elastic section modulus is 0.0491 inch$^3$, the plastic section modulus 0.0543 inch$^3$. It was determined by means of static tests on tensile specimen that the static yield strength of SAE 1020 steel is 37,500 psi. The theoretical moment capacities of the beams are thus

\[ M_{\text{yield}} = 37,500 \times 0.0491 = 1830 \text{ inch pound} \]

\[ M_{\text{plastic}} = 37,500 \times 0.0543 = 2040 \text{ inch pound} \]

The total load $P$ which is required to cause these moments is given by

\[ P_{\text{yield}} = 0.333 \times M_{\text{yield}} = 610 \text{ pounds} \]

\[ P_{\text{plastic}} = 0.333 \times M_{\text{plastic}} = 680 \text{ pounds} \]
The static test results, which are summarized in Figure D.1, show good agreement with the load values that are computed above. In addition to the average curve for the three static tests, two hypothetical load-deflection curves are shown in Figure D.1. These are the estimated dynamic resistance functions corresponding to a 10% and a 20% increase in the yield strength of the steel due to strain rate effects.

Three dynamic tests have been performed. Beams D.4 and D.5 were tested at a nominal pressure of 60 psi, beam D.6 at a pressure of 65 psi. The experimental load-time and deflection-time curves are presented in Figure D.2. The results for beams D.4 and D.5 are essentially identical, indicating a maximum deflection of 0.21 inches. Beam D.6, due to the slight increase in the applied load, shows a very considerable increase in the maximum deflection, which now becomes 0.48 inches. The experimental results are compared to theoretical predictions which have been obtained as described in appendix A. Note that the weight of the beams has changed to 0.855 pounds. Three different resistance functions are considered, corresponding to the three load-deflection curves presented in Figure D.1. The static resistance function leads to predicted maximum deflections which are considerably larger than the experimental values. If a 20% increase in the yield strength due to strain rate effects is assumed for beams D.4 and D.5, the theoretical and experimental maximum deflections are seen to be in good agreement. For beam D.6, the increase in the yield strength seems to be of the order of 15%.

It may be concluded from the results of this test series that the resistance function for bending of beams manufactured out of SAE 1020 steel is strain rate dependent. The resistance functions of the SAE 1113 steel models in bending proved to be independent of the strain rate, even though the tensile tests described in section 3.4 indicated a significant increase in the yield strength for strain rates of the order of 0.1 inch/inch/second. It is noted that the static yield strength of the SAE 1020 steel (37500 psi) is considerably lower than that of the
FIGURE D.1
STATIC BEHAVIOR OF BEAMS D.1 TO D.3
FIGURE D.2
DYNAMIC BEHAVIOR OF BEAMS D.4 TO D.6
SAE 1113 steel (62500 psi), and that the two materials differ in their chemical composition. On the basis of the control tests described in this appendix D, it seems reasonable to assume that the results for the SAE 1113 models described in the main part of this report reflect the specific properties of SAE 1113 steel.
REFERENCES


The objective of this research project is the development of modelling techniques for steel structures and an investigation of the effect of strain rate on the resistance function of structural elements. The work proceeded in four phases: a dynamic loading machine was developed, dynamic material properties were determined in a series of tensile tests, 16 static and dynamic tests were performed on simply supported beams loaded at the third points, and a series of 16 static and dynamic tests were performed on fixed ended portal frames subjected to a lateral load at the level of the girder.

The dynamic loading machine is capable of rise times of 3 milliseconds or more and maximum loads of 2000 pounds. It can also be used as a static loading machine.

Generally, it is concluded that model studies of steel structures provide an excellent experimental tool. Very sensitive tests for the investigation of strain rate effects have been developed. The necessary apparatus and techniques have been refined and initial difficulties eliminated so that a large number of additional tests on models with a variety of geometric configurations and material properties could be performed rapidly and reliably. These tests might significantly extend our understanding of the dynamic behavior of steel structures.
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