01 Apr 1991

Study of Joint Flexibility in Steel Frame Structures

Randy R. Frank

STUDY OF JOINT FLEXIBILITY IN STEEL FRAME STRUCTURES

Randy R. Frank

I. ABSTRACT

Joint flexibility plays an important role in the distribution of strains and displacements in the frame structures of buildings, towers, automobiles, etc.. The objective of this project is to study the effect of flexibility (or rigidity) of two simple mechanical joints in frame structures on the stress and displacement distributions, using both experimental and analytical methods. Three welded and three bolted samples were fabricated using A-36 low carbon steel in a two column and horizontal cross-member (table) arrangement. This arrangement allows for both shear forces and axial forces in the joint. From a three element rectangular rosette strain gage attached to the bottom of the cross-member, strain readings were collected by a computer based data acquisition and processing system, during point and line loading (elastic range) of the specimens by a load frame. These results were compared to each other and to values found by analytical methods for the same arrangement with theoretically rigid and theoretically completely flexible joints.

The data for the line loading of the samples were plotted and compared with the analytical results. Also a quantitative flexibility index was developed and used to compare the bolted and welded joints. The flexibility index is defined as the ratio of the difference between the actual and theoretical rigid joint flexibility to the difference between the theoretical flexible joint and the theoretical rigid joint flexibility in percentage. These comparisons were made for each sample at load increments over 50 lbs and within the elastic limit of the specimen. This was chosen because of the linear relation of the data received in this range and the slight error of the experimental apparatus at low loads. The test was conducted for each of the six specimens of the bolted and welded joints (3 specimens per joint type) and then repeated. This allowed for error in the measurement and in the manufacture of the specimens. The average flexibility index for the bolted joint samples (line loading) were 52.23%, 50.46%, and 46.6% resulting in a total average flexibility index of 49.73% with standard deviation of 3.21. The average flexibility index for the welded joint samples (line loading) were 46.38%, 42.95%, and 42.27% resulting in a total average flexibility index of 43.87% with standard deviation of 2.78. The data from the point loading runs were used to see if anything unusual happened in this case. Because of averaging by the strain gage of the values of the strain at the center due to the stress concentration of a point loading the values were not used to compute a flexibility index. There were no unusual findings from the point loading data.

The results show that the bolted joints used in this experiment were more flexible than the welded joints for both line and point load. Furthermore, both joints did not act as completely flexible or completely rigid joints. This fact confirms the importance of the joint flexibility consideration in the design of steel frame structures.

II. INTRODUCTION

Steel frame structures are commonly used in the construction of buildings, bridges, towers and automobiles. An important aspect to the effective and efficient design of a frame structure is the flexibility in the joints. Most design theory does not account for the flexibility in joints. Thus, once an engineer has designed a frame structure, extensive testing would need to be performed to verify his design. This often results in redesign of the joints to reduce or increase the flexibility followed by further testing. This iterative process increases the development time and cost of the frames.

The objective of this project is to study the effect of flexibility (or rigidity) of two simple mechanical joints in frame structures on the strains and displacement distributions, using both experimental and analytical methods.

Figure 1 shows the design and dimensions of a bolted and welded steel frame structures subjected to flexure, which will be investigated in this research. From the literature survey conducted, no published literature was found on joint flexibility on frame structures which have elements subjected to flexure. Most of the published work found were limited to single plate framing shear connections, which consists of a plate welded to a support at one edge and bolted to a beam web [1,2].

Joint flexibility of frame structures subjected to flexure must be known to make efficient and effective design. Testing would be too time consuming and expensive in today's competitive markets. Standard sized bolted, welded, riveted and glued joints should be tested to evaluate the flexibility. Their flexibility should be indexed to allow comparisons between different joint types. The flexibility index information could be compiled and used as a reference for engineers when they design frames. Some indexing has been developed by some finite element software manufactures. They have setup an index called the Degree of Fixity, which is an index from 0-1 of how rigid a joint acts [3]. A rigid joint is given a value of 1. This index would be used in the finite element program to help model the actual stresses and displacements. The index was only done for four general categories of joints. In this research, an index will be developed to aid in comparison of the joints to different joints and to theoretical values of the joint flexibility Bolted and welded joints in a steel frame structures will be investigated.

III. SPECIMEN DESIGN AND ANALYSIS

General specimen: Three welded and three bolted samples were fabricated using A-36 low carbon steel in a two column and horizontal cross-member (table) arrangement. The specifications of the designs are shown in figure 1a and figure 1b for the bolted and welded joint respectively. This arrangement allows for both shear forces and axial forces in the joint. The legs of the table arrangement were designed to be rigid and the top plate to be flexible. Thus the thickness of the legs were chosen to be much greater than the thickness of the top plate. The top plate thickness and the distance between the legs were chosen by the relationship shown in equation (1) [4].

$$\frac{\text{Span between the legs } (l)}{\text{Top plate thickness } (t)} >= 100 \qquad (1)$$

The total length of the specimen was constrained by the size of the test equipment, corresponding to the leg span (l) being chosen as 12.5 inches. The thickness of the top plate (t) was then found by using equation 1 to be 0.125 inches. The requirement of equation (1) is then satisfied by $l/t = 12.5/0.125 = 100$. Standard sizes of material could now be used to fabricate the specimens.

Material: The material used was low carbon ASTM A-36 plate steel with properties shown in table 1 [5]. This material is widely used in frame structures and in general applications [1,2]. Therefore, it was readily available at a local welding shop for very low cost. Other types of materials proved to be too expensive be considered in this project.

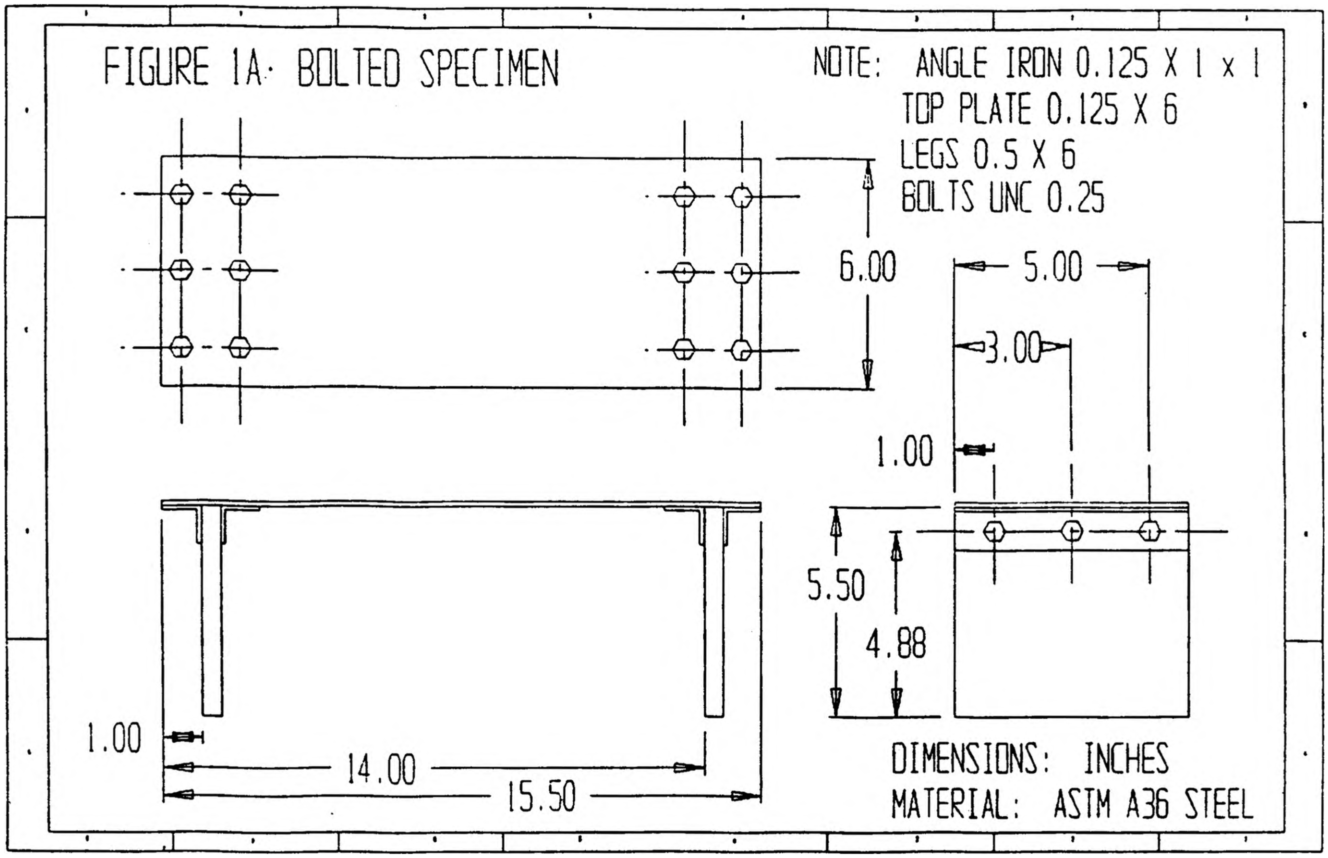


FIGURE 1A· BOLTED SPECIMEN
NOTE: ANGLE IRON 0.125 X 1 x 1
TOP PLATE 0.125 X 6
LEGS 0.5 X 6
BOLTS UNC 0.25
6.00
5.00
3.00
1.00
5.50
4.88
1.00
14.00
15.50
DIMENSIONS: INCHES
MATERIAL: ASTM A36 STEEL

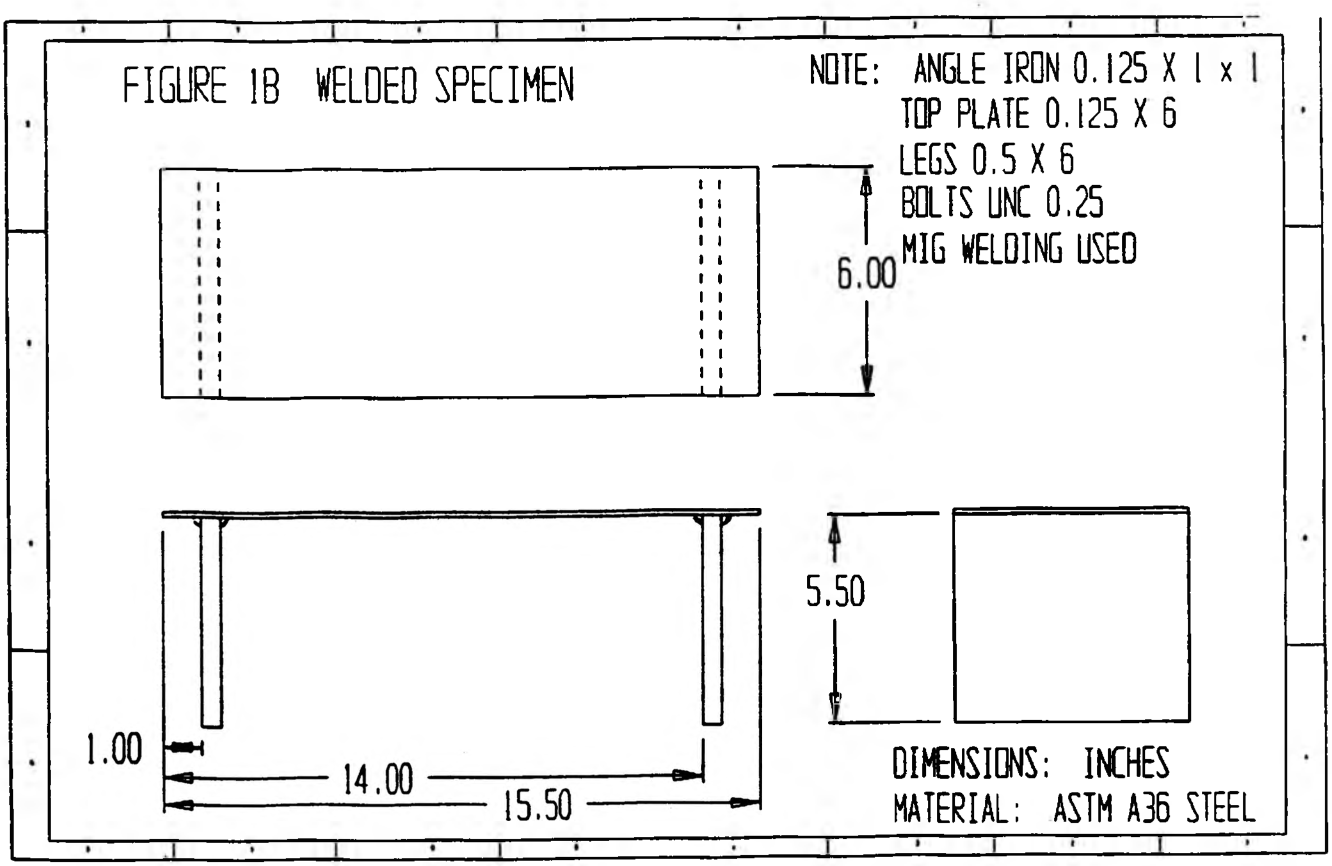


FIGURE 1B WELDED SPECIMEN
NOTE: ANGLE IRON 0.125 X 1 x 1
TOP PLATE 0.125 X 6
LEGS 0.5 X 6
BOLTS UNC 0.25
MIG WELDING USED
6.00
5.50
1.00
14.00
15.50
DIMENSIONS: INCHES
MATERIAL: ASTM A36 STEEL

Table 1 PROPERTIES of TEST SPECIMENS: ASTM A-36 ASME SA36 LOW CARBON STEEL	
Tensile Strength (S_u)	65 KSI minimum
Yield Strength (S_y)	50 KSI minimum
Inertia of top plate (I)	0.0009765 in^4
Top plate thickness (t)	0.125 inches

Loading: Typically in frame design plastic deformation is undesirable. Therefore it is necessary to find the loading limits for the design. A safety factor of 2 for the specimen was chosen for maximum loading. This will guard against any accidental permanent deformation of the sample specimens.

The top plate, being the weakest pint in the specimen, will dictate the maximum load that can be applied to the specimen. Figure 2a shows a line force at the center of the top plate of the specimen acting downward parallel to the legs. The shear force and bending moment were found as a function of the applied line force (F) to the specimen as shown in figures 2b and 2c respectively. The maximum force (F_{max}) to be applied to the specimen was obtained from the maximum bending stress [2,8] given in equation (2).

$$S_{max} = \frac{S_y}{2} = \frac{M_{max}c}{I} \qquad (2)$$

where (S_y) is the yield strength of the material and 2 is the factor of safety, (M_{max}) is the maximum bending moment, (c) is half of the top plate thickness (t/2) and I is the moment of inertia. The maximum bending moment (M_{max}) is obtained from figure 2c and is expressed as:

$$M_{max} = (F/2)X6.25 \qquad (3)$$

The maximum force (F_{max}) that could be applied to the specimen was then obtained by substituting equation (3) into equation (2):

$$F_{max} = \frac{S_y I}{6.25c} \qquad (4)$$

Substituting the values for yield strength (S_y), the inertia (I) and half of the top plate thickness (c), from table 1, the maximum loading force obtained was F_{max} = 125 lbs.

The force that could be applied for the point load was obtained in a similar fashion by replacing the line load with the point load in figure 3. The force obtained was the same as for the line load case.

Bolted Specimen Design: The main consideration in the bolted specimen was joint separation. It was assumed that the bolts should be strong enough to keep the joint from separating when loaded to the maximum force. This was done by making a few simple conservative assumption to find the deflection angle of the top plate (Theta) under maximum loading conditions with no bolts present

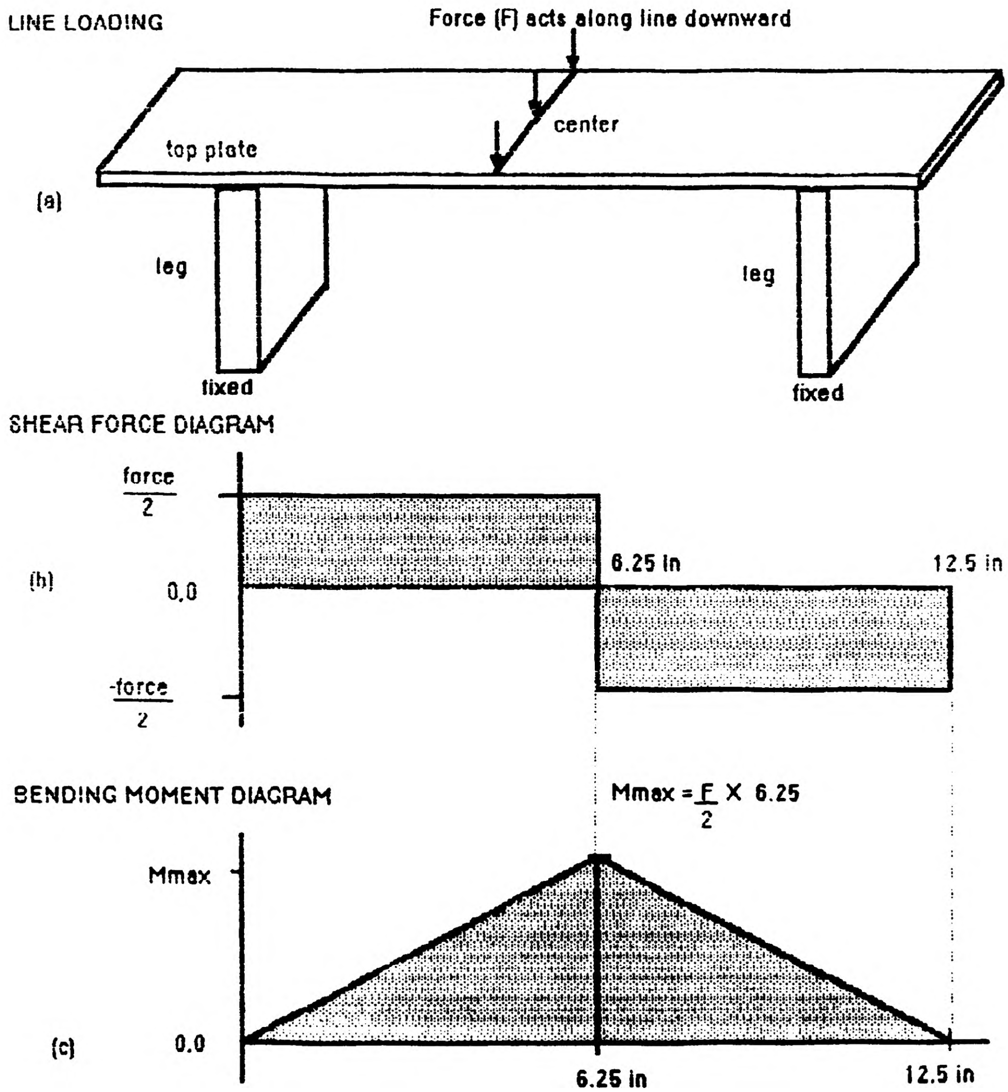


FIGURE 2 LINE FORCE LOADING, SHEAR FORCE and BENDING MOMENT DIAGRAMS.

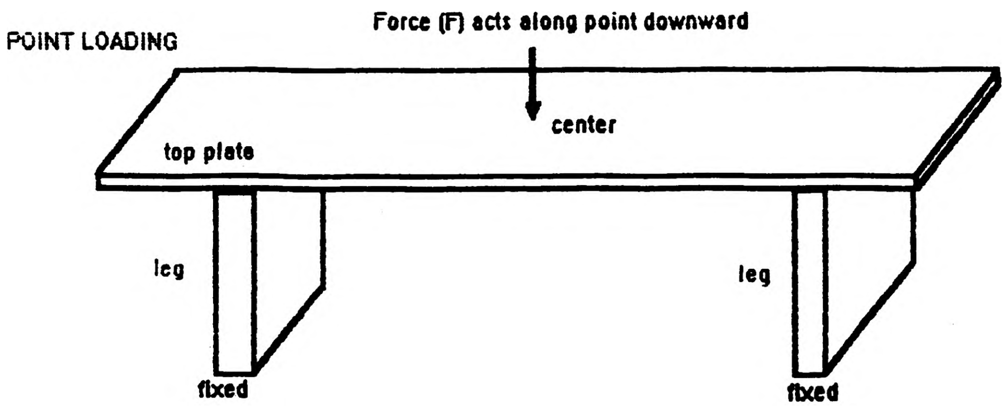


FIGURE 3 POINT LOADING OF SPECIMEN.

and the corresponding bolt force necessary to keep the joint from separating. This calculation was done using equation (5) [8] by substituting values of 125 lbs for the maximum force applied (F), 12.5 inches for the span length (L), 30,000 KSI for Young's Modulus (E) and 0.0009765 for the inertia (I). Therefore, Theta was found to be $\theta = 125x(12.5)^2/(16x30E6x0.0009765) = 0.04167$ radians.

$$\theta = \frac{FL^2}{16EI} \tag{5}$$

The force necessary to bring the plate back to a horizontal position or no joint separation was calculated to estimate the force necessary for the bolts to withstand under maximum loading conditions. Using trigonometry and the computed θ value of 0.01467 radians and distance to the bolts the distance needed to return the plate to a horizontal position (Y) was found to be 0.04165 inches. Thus, the force necessary for the bolts to withstand (P) was found using equation (6) [8]. Values for Young's Modulus (E) and inertia (I) were taken from above to give $P = (3x30E6x0.0009765x0.04165)/(12.5)^3 = 1.87$ lbs.

$$Y = \frac{PL^3}{3EI} \tag{6}$$

Stresses calculated using three 1/4 inch bolts on each side of the joint were found to be much less than the yield strength of the bolts. The shear stresses in the bolts through the legs were calculated and also found to be much less than the yield strength of the bolts. To confirm proper design of the bolted joint, it was checked using a procedure from a article Machine Design by Edmund J. Gohmann, Jr. of Purdue University [6]. Using Gohmann's procedure it was confirmed that joint separation (failure), under the maximum loads, would not occur. The drawing of the final bolted joint design used in this project is shown in figure 1a.

Welded Design: The welded joint was done using Metal Inert Gas Welding (MIG) to weld the joint on both sides of the legs to the top plate. This allowed for a smooth continuous weld to the thin top plate. The final drawing of the welded design used in this project is shown in figure 1b. Note that the overall dimensions are the same as the bolted design shown in figure 1a.

Strain Gage Selection: A strain gage was needed in order to record the strain at the center of the top plate of each specimen at different load levels. A six step procedure was used in the selection of an appropriate gage for this application. The procedure was taken from Measurements Group, Inc. Bulletin 309B [7,10]. This procedure resulted in picking a 3 element rectangular rossette strain gage (specification: CEA-06-250UR-120) from Micro-Measurements Division of Measurements Group, Inc..

Theoretical Analysis: Values for strain of the specimen under theoretically rigid and completely flexible joints were used for an analytically analysis of the data. Values for the strain at the bottom center of the top plate were found using equation (2), for a theoretically completely flexible joint. These values were complied by a software program written in basic. Strain values for a theoretically rigid joint were found using the deflection at the center of a beam rigidly held (at the end of the span between the legs) and a trigonometric relationship. The deflection at the center of a theoretically rigid joint specimen was found using equation (7) [9].

$$Y = \frac{FL^3}{192EI} \tag{7}$$

Where (Y) is the deflection at the center, (F) is the force applied, (L) is the span between the legs, (E) is Young's Modulus and (I) is the inertia. The strain was found using the relationship between right triangles to find the change in length of the top plate divided by the original length of the top plate. These values were compiled by a software program written in basic.

Flexibility Index: To compare the experimental results with the analytical results, a flexibility index was developed. The flexibility index (FI) is defined as the ratio of the difference between the actual and theoretical rigid joint flexibility to the difference between the theoretical flexible joint and the theoretical rigid joint flexibility in percentage. The flexibility index is expressed as:

$$FI = \frac{((\text{Actual flexibility})-(\text{Rigid flexibility}))}{((\text{Flexible flexibility})-(\text{Rigid flexibility}))} \tag{8}$$

The FI were computed for each sample at load increments over 50 lbs and within the elastic limit of the specimen. This was chosen because of the linear relation of the data received in the range and the slight error of the experimental apparatus at low loads. An average value of the FI was calculated for each test run. The data collected in this experiment was confirmed by multiple repetitions of each sample and by multiple samples. This allowed for correction of error in manufacture and measurement.

IV. EQUIPMENT AND EXPERIMENTAL PROCEDURE

Equipment: A computer based data acquisition and processing system was used to collect the data when the specimen was continuously loaded in a load frame. The computer read data from four channels. One channel was used for recording the load applied to the specimen. The other three channels were connected to strain indicators that were attached to each of the three elements of the rossette gage. This information was stored on disk for later evaluation. The software used in the data acquisition system was developed by Dr. Hornsey for the Basic Engineering Laboratory.

Procedure: The specimen was placed in the holding fixture and put in the load frame. The strain gage was connected to the strain indicator using a quarter bridge arrangement. Using two leads from one tab of the stain gage it was possible to connect the gage so that it was not sensitive to the lead wires. The gages were set to the proper gage factor of 2.06 and zeroed. The longitude gage was hooked to data channel 1 of the data acquisition system. The load applied, 45 degree gage and the transverse gage were hooked to data channels 0,2,3 respectively. The data collection program (Univrsl.tst) was executed. The load range setting was set for the 0-600 lb range. Strain ranges were set to 0-600 microstrain. A calibration was done for the collection equipment. This allows the software to set conversions for each channel so that the readings match the load readout and strain readouts on the equipment. The loading was done using a round bar placed horizontally on top of the plate under the load cell to apply a line load. A point load was achieved by using a ball bearing in a similar fashion. Data collection was done at equal increments of load under a continuous loading of the specimen. Loading started at 5 lbs and continued to 125 lbs. After finishing a test the data was loaded into a file on disk. This data file was converted to a more usable format and loaded into a graphing program for graphical results. The file was also used by a program in basic which converted the values to FI for each increment. An overall average value of the FI for each test was also calculated. This procedure was repeated for all test of the specimens.

V. EXPERIMENTAL RESULTS

Line Loading: The line loading was run twice for each of the three specimens. The resulting data was then plotted using strain versus load for each run. A qualitative analysis of the plotted data was done to compare the flexibility of the bolted and welded joints. It was found that the bolted joint exhibited higher values of strain for equal loads. In general the bolted joint was more flexible than the welded joint. The flexibility index, developed in Specimen Design and Analysis, was used to quantitatively analyze the data. The average flexibility index for the bolted joint samples were 52.23%, 50.46% and 46.6% resulting in a total average flexibility index of 49.73% with standard deviation of 3.21. The average flexibility index for the welded joint samples were 46.38%, 42.95% and 42.27% resulting in a total average flexibility index of 43.87% with a standard deviation of 2.78. The individual average flexibility indexes for each sample were plotted versus load for the bolted and welded joint specimens in figure 4 and figure 5 respectively.

Point Loading: The point loading was run twice for each of the three specimens. The resulting data was plotted using strain versus load for each run. Like in the line loading case a qualitative analysis was done using these plots. The bolted joint was again more 'flexible' then the welded joint. A quantitative analysis was not done on this data because values for the theoretical cases were derived using a line loading of the sample. The purpose of the point loading was to qualitatively confirm the line loading data.

VI. CONCLUSIONS

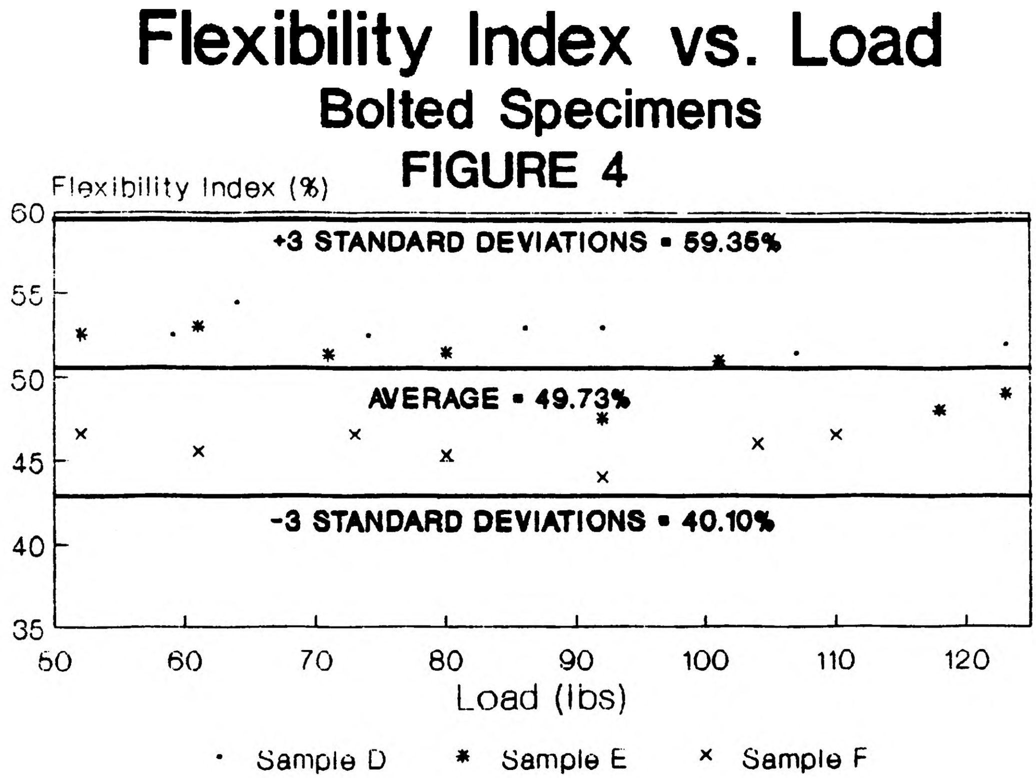
Based on the studies report here, the following conclusions were reached:

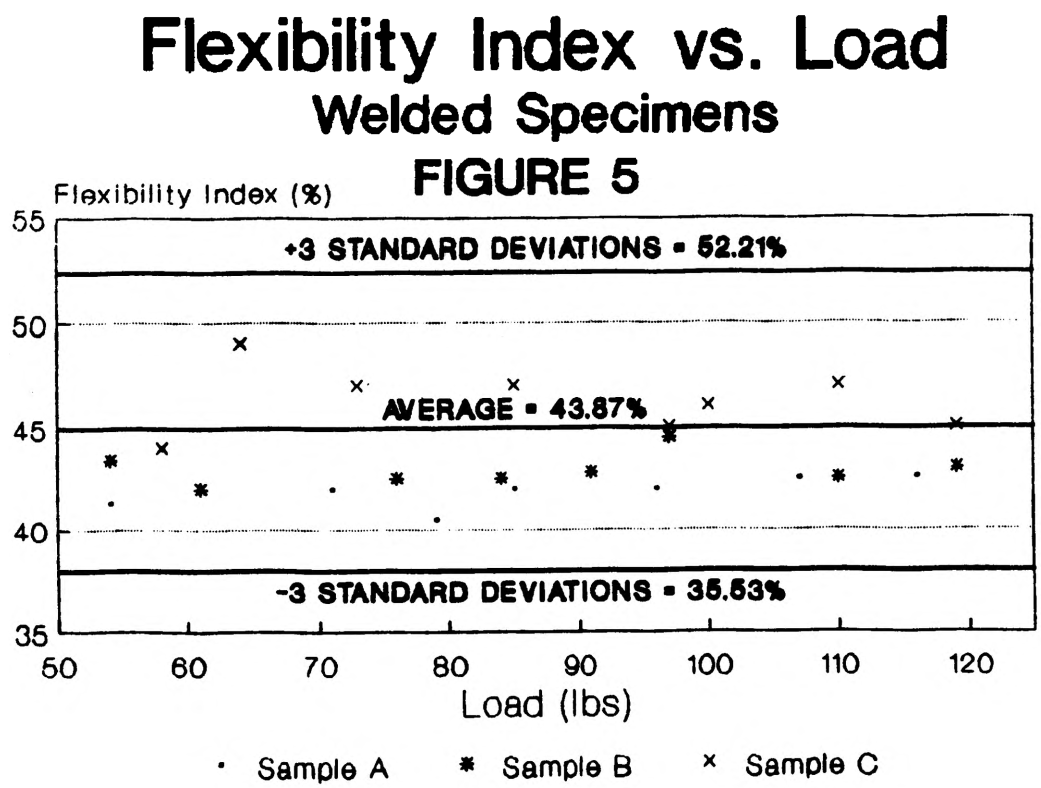
1. The bolted joints used in this experiment were more flexible than the welded joints for both line and point loading. Both joints did not act as a completely flexible or completely rigid joints. This fact confirms the importance of the joint flexibility consideration in the design of steel frame structures.

2. The flexibility indexes were converted to the degree of fixity and were found to meet the specifications given for the welded and bolted categories by the software manufacturer.

3. It is recommended that standards should be setup for joint flexibility. This could be done using the flexibility index developed in this experiment or by using the degree of fixity used by some finite element software manufactures.

4. The average flexibility index for the bolted joint samples were 52.23%, 50.46% and 46.6% resulting in a total average flexibility index of 49.73% with standard deviation of


Flexibility Index vs. Load
Bolted Specimens
FIGURE 4
Flexibility Index (%)
+3 STANDARD DEVIATIONS = 59.35%
AVERAGE = 49.73%
-3 STANDARD DEVIATIONS = 40.10%
60
55
50
45
40
35
50
60
70
80
90
100
110
120
Load (lbs)
Sample D
Sample E
Sample F


Flexibility Index vs. Load
Welded Specimens
FIGURE 5
Flexibility Index (%)
+3 STANDARD DEVIATIONS = 52.21%
AVERAGE = 43.87%
-3 STANDARD DEVIATIONS = 35.53%
55
50
45
40
35
50
60
70
80
90
100
110
120
Load (lbs)
Sample A
Sample B
Sample C

3.21. The average flexibility index for the welded joint samples were 46.38%, 42.95% and 42.27% resulting in a total average flexibility index of 43.87% with a standard deviation of 2.78.

5. Further work is proposed to evaluate the effect of different plate thickness, beam thickness, span to thickness ratio, number of bolts and type of weld.

VII. ACKNOWLEDGEMENTS

The project was performed using the equipment in the Basic Engineering laboratory. The availability of the data acquisition system in the laboratory enable more accurate results to be obtained. The use of the laboratory equipment and support in execution of the experiment provided by Dr. Edward E. Hornsey was sincerely appreciated. Special thanks also go to Bob Hribar and Ken Schmid both of mechanical engineering department who helped in fabricating the test specimens and mounting the strain gages respectively.

VIII. REFERENCES

1. A. Astanch, S.M. Call and K. M. McMullin, "Design of Single Plate Shear Connections", Engineering Journal, American Institute of Steel Construction, First Quarter 1989. pp 21-32.

2. R. M. Richard, P.E. Gillett, D. Kreigh and B. A. Lewis, "The Analysis and Design of Single Plate Framing Connections", Engineering Journal, American Institute of Steel Construction, 2nd Quarter 1990, pp 38-52.

3. International Business Machine, Computer-Aided Engineering Design System Analysis, (CAEDS), Users Manual, 1984.

4. Young W. Kwon, Assistant Professor, Naval Post-Graduate School, Monterey, California.

5. Joseph T. Ryerson & Sons Inc., Ryerson Stock List & Data Book, 1987-88 Edition, pp 386.

6. E. J. Gohmann, Jr., "Evaluating Loads in Bolted Joints", Machine Design, January 22, 1987, pp 103.

7. Measurement Group Inc., "Student Manual for Strain Gage Technology, Bulletin 309B, 1983.

8. Higdon, A., E.H. Ohlsen, W.B. Stiles, J.A. Weese, W.F. Riley, Mechanics of Materials, Fourth Edition, 1985, pp 65-124, 708.

9. J.E. Shigley, C.R. Mischke, Mechanical Engineering Design, Fifth Edition, McGraw - Hill, 1989, pp 325-405, 741.

10. J.W. Dally, W.F. Riley, Experimental Stress Analysis, Second Edition, McGraw - Hill, 1978, pp 153-163, 318-329.