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TESTS ON ECCENTRICALLY LOADED FILLET WELDS

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ABSTRACT

The ultimate strength of eccentrically loaded fastener groups is now used as the basis for design recommendations in both Canada and the United States. As outlined by Butler, Pal and Kulak, the method for connections using fillet welds and loaded in-plane is based on fulfillment of the equilibrium and compatibility conditions and on recognition of the true shear load versus shear deformation of the fillet weld. The analytical method had been substantiated by a series of tests on full-size connections in which the fillet welds were either vertical or arranged in a C-shaped fashion.

More recent tests than those reported by Butler, Pal and Kulak have been provided by a study sponsored by the Australian Welding Research Association. The test results obtained in this program generally confirmed the analytical predictions, but correlation for some specific tests is poor. These particular tests used fillet welds arranged horizontally, a configuration not previously tested. The program reported herein was therefore set up to examine this weld arrangement. Three full-size tests of eccentrically loaded fillet welded connections and a number of corresponding weld coupon tests were carried out. The method of Butler, Pal and Kulak was used to predict the ultimate load of the full-size pieces and good correlation between test load and predicted load was achieved in each case.

Acknowledgements

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Introduction

The ultimate strength of eccentrically loaded fastener groups is now used as the basis for design recommendations in both Canada (1) and the United States (2). As outlined by Butler, Pal and Kulak (3), the method for connections using fillet welds and loaded in-plane is based on fulfillment of the equilibrium and compatibility equations and on recognition of the true shear load versus shear deformation of the fillet weld. The analytical method had been substantiated by a series of tests on full-size connections in which the fillet welds were either vertical or arranged in a C-shaped fashion.

More recent tests than those reported by Butler, Pal and Kulak have been provided by a study sponsored by the Australian Welding Research Association (4). The test results obtained in this program can generally be confirmed by the analytical predictions made using the method outlined in the CISC Handbook* (adjusted to give ultimate resistance, not factored resistance), but corrolation for some specific tests is poor. These tests used fillet welds arranged horizontally, as shown in Fig. 1. Because the results reported by Butler, Pal and Kulak did not

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* The Canadian Institute of Steel Construction "Limit States Design Steel Manual", published in 1977, and the Canadian Institute of Steel Construction "Handbook of Steel Construction", published in 1980, contain essentially the same information with respect to eccentrically loaded weld groups with two exceptions. One is that the Manual is set up for Imperial units while the Handbook uses S.I. units. The second is that the Manual contains tabulated coefficients for the case of horizontally placed fillet welds, but this case is not contained in the Handbook. In this report, reference will generally be made to the Handbook (1). However, when dealing specifically with horizontally placed fillet welds, the reference will be to the Manual (5).

include this configuration, it was considered advisable to conduct additional physical tests. The objectives of the program described herein were, therefore, to provide test results for fillet weld arrangements of the type shown in Fig. 1, loaded in-plane, so as to provide further evidence as to the suitability of the method used in the Canadian Institute of Steel Construction Handbook of Steel Construction (1). The test program was sponsored by the Canadian Steel Construction Council.

Scope

The strength of any fillet weld group obviously is dependent upon the strength of the deposited weld material. Rather than rely upon the use of specified minimum strength and ductility values for the weld electrode or use the results of previous calibration tests, it is advisable to carry out shear load versus deformation tests for deposited weld metal conforming as closely as possible to that which is to be used in the fabrication of any full-size specimens. Accordingly, five weld coupons were prepared and tested for this program. A description of these coupons and the test results is given subsequently.

Three full-size specimens in which fillet weld groups would be loaded eccentrically were prepared and tested. Each specimen was detailed so as to test two identical connections, one on each side of a beam web. The descriptions of the specimens, testing procedure, and results are given later in this report.

Review of Analytical Method

For completeness, a review of the analytical method that will be used to predict the test results is provided in this section. It is adapted from the work of Butler, Pal and Kulak (3).

Assumptions in the Analysis

1. A continuous fillet weld can be considered to be made up of a series of elemental lengths of fillet welds. Each elemental length is assumed to resist applied forces through its centroid.

2. The strength properties of fillet welds are assumed to be proportional to their leg size.

3. The strength and deformation properties of the fillet weld are assumed to be independent of whether the shear is induced by a compressive load or by a tensile load (Fig. 2).

4. In a weld group, the deformation of each element of weld will vary linearly with its distance from the instantaneous center of rotation and the deformation will take place perpendicularly to the radius of rotation.

5. The ultimate strength of the group will be reached when the deformation capacity of any elemental length of weld is

reached.

Description of the Model

The description given herein is shown for the specific case of horizontally-located fillet welds. The method is not restricted to this case, however.

Figure 1 shows the eccentrically loaded weld group and its idealization. For the case wherein the load vector is perpendicular to one of the principal axes of the weld arrangement, it can be shown that the instantaneous center of rotation lies on a line passing through the center of gravity and perpendicular to the load vector. The location of the instantaneous center of rotation on this line must be determined by trial.

The distance from this instantaneous center to any weld element is given by (see Fig. 1)

$$r_n = \sqrt{(x_n + r_o)^2 + y^2} \qquad (1)$$

and the angle that the resultant force on any element makes with the longitudinal axis of the weld is given by

$$\theta_n = \tan^{-1} \frac{x_n + r_o}{y} \qquad (2)$$

The first element of weld which reaches its ultimate deformation must be located. (Usually, but not always, it is the one furthest from the instantaneous center of rotation.)

Mathematically, it is the one for which the ratio of ultimate deformation to radius of rotation is a minimum. Calling this deformation Δ_{max} and using the value of the angle calculated from Eq. 2, the following empirical relationship can be used to obtain the ultimate deformation (mm) for any element (3);

$$\Delta_{max} = 5.97\ (\theta + 5)^{-0.47} \tag{3}$$

where θ is expressed in degrees. (Eq. 3 is not a direct conversion of U.S. Customary Units to S.I. of the corresponding equation given in Ref. 3. The new data obtained from the weld coupon tests in the study reported herein were used to improve the empirically-derived expression.)

The ratio just described can now be examined and the critical element located.

Because the deformation of each element of weld is assumed to vary linearly with its distance from the center of rotation, the deformation of any other element is given by

$$\Delta_n = \frac{r_n}{r_{max}}\,\Delta_{max} \tag{4}$$

in which r_{max} = the radius of rotation for the element of weld which first reaches its ultimate deformation.

The resisting force, R_n, acting at the center of the nth element and at an angle θ, in degrees, can then be found from

$$R_n = R_{ult}\left(1 - e^{-\mu\Delta_n}\right)^{\lambda} \tag{5}$$

The values of R_{ult}, μ, and λ will depend on the value of the angle θ and are found from the following empirical equations (3):

$$R_{ult} = \frac{10 + \theta}{5.864 + 0.341\theta} \tag{6}$$

$$\mu = 2.953\ e^{0.0114\theta} \tag{7}$$

$$\lambda = 0.4\ e^{0.0146\theta} \tag{8}$$

In these equations, e is the base of natural logarithms.

The vertical component of the resisting force on each element of weld can be calculated from the geometry of the connection. For elements in the horizontal leg:

$$(R_n)_v = R_n \sin \theta_n \tag{9}$$

The equations of equilibrium can now be checked, namely:

$$\Sigma F_x = 0 \tag{10}$$

$$\Sigma F_y = 0 \tag{11}$$

$$\Sigma M = 0 \tag{12}$$

Because there are no external forces in the x-direction, Eq. 10 is automatically satisfied. From Eq. 12, the externally applied load, P, can be found by taking the sum of the moments about the instantaneous center:

$$P(e + r_o) - \sum_{n=1}^{n} (r_n \times R_n) = 0 \qquad (13)$$

In order to satisfy Eq. 11, load P as found from Eq. 13 must be equal to the sum of the vertical components R_v calculated using Eq. 9, that is

$$P - \sum_{n=1}^{n} (R_v)_n = 0 \qquad (14)$$

If Eq. 14 is not satisfied, a new trial location of the instantaneous center must be chosen, and the procedure repeated. When a value of r_o is found which satisfies the equations of statics, the value of P so obtained is the ultimate load which the weld group can sustain.

Experimental Study

Weld Coupons. - In order to establish the shear load versus deformation response of the deposited weld metal, a series of five weld coupons were tested. For these tests, the load vector was parallel to the longitudinal axis of the weld in all cases ($\theta = 0°$). It was assumed that the parameters for other values of θ would be proportional to this base value.

The coupons were made using plate from the same rolling that was subsequently used to fabricate the angles used in the full-size tests described below. The plate was 25 mm thick and met the requirements of CSA G40.21M 300W. All nominal 6.35 mm leg size (1/4 in.) fillet welds were made using E480 electrodes obtained from the same lot and all welds were made in one pass by the same operator. Weld returns and runoffs were milled or sawn free prior to testing. Figure 2 shows the weld coupon and Table 1 gives the weld lengths and averaged leg sizes as obtained from plaster casts made of each weld run.

The coupons were loaded by applying a tension load to the specimen. A transducer was mounted on each specimen so as to measure the average shear deformation of the four fillet weld runs (two on each side of the coupon). It was considered that the amount of plate deformation measured in the test setup was negligible. A continuous plot of load versus deformation was obtained during the test. All failures occurred through the least cross-sectional area, that is, through the throat of the weld.

The shear load at failure (kN per mm of weld length for a leg size of 6.35 mm) is shown in Table 1 for all five weld coupons. The 6.35 mm leg size (i.e. 1/4 in.) was chosen as the standard of comparison simply because this is what had been used in earlier studies. Table 1 also lists the deformation at failure, Δ_{max}, for each test.

Figure 3 shows the complete test results for all weld coupons. Also shown is the form of Eq. (5) which best fits the test results.

Full-Size Specimens. - The arrangement of the full-size eccentrically loaded test specimens is shown in Fig. 4 and a photograph of an actual specimen is shown in Fig. 5. The diagonal stiffener was not part of the original test detail but had to be added due to shear buckling of the web in that region. Figure 6 summarizes the dimensions (nominal) used for the weld arrangements used in the three test pieces. The terminology used follows that used in the CISC Handbook.

Table 2 lists the actual weld lengths and fillet leg sizes and summarizes the test results. Although the actual average weld length and fillet leg size have been listed, the loads recorded in Table 2 have been adjusted to correspond to a fillet weld leg dimension of 6.35 mm. Thus, the load in Col. (4) of the table is the test load for one weld arrangement of the type shown in Fig. 6 and for which 6.35 mm fillet legs are present. The load listed in Col. (5) is the corresponding load that would be predicted by the method described herein, using the actual weld properties as obtained from the weld coupon tests. Col. (6) lists the per cent error between the two results, assuming that the "correct" load is the test load. It can be observed that the predicted loads are all reasonably close to the corresponding test values and that all predictions are on the conservative side.

Prediction of Test Results using CISC Manual

In the Introduction, it was noted that tables contained in the CISC Manual (5) could be used to calculate permissible loads on horizontally oriented fillet weld groups. Table 3 summarizes the values obtained using the Manual. Listed again is the test load for the specimens reported herein. Column (3) gives the loads obtained using the Manual; these are the factored resistances ascribed to the connection. As can be seen, they are substantially below the test loads. Column (4) lists predictions of the test loads which can be obtained using the Manual. The per cent error between these values and the test loads is given in Col. (5).

The method used in the Manual to develop the factored resistance for a connection takes the basic weld strength (θ=0° case) as that corresponding to the limit provided in CSA S16.1-M78, Clause 13.13.1, namely

$$V_r = 0.50\ \phi\ A_w\ X_u \qquad (15)$$

where ϕ = the performance factor, taken as 0.90

A_w = effective throat area of weld

X_u = ultimate strength as rated by electrode classification number.

The product $0.50\phi = 0.50 \times 0.90$ is expressed more fundamentally as (6) 0.67×0.67. The second of these two identical terms is the performance factor usually assigned to connectors and the first term relates weld shear strength to electrode ultimate strength. The use of Eq. (15) is known to give conservative results. This can be seen by comparing the values of factored resistance, Col. (3) of Table 3, with the test values, Col. (2). Another basis of comparison is to compare the basic weld strength predicted using Eq. 15 with the weld coupon test results reported herein. For E480xx electrodes, Eq. 15 predicts a weld capacity of 0.97 kN/mm for a 6.35 mm fillet, whereas the weld coupon results given in Table 1 show an average weld strength of 1.71 kN/mm. It can be expected, therefore, that the factored resistance calculated using the CISC Manual will be considerably less than the actual ultimate strength. For the connections reported in Table 3, this margin is in the order of 2.

The factored resistances calculated using the CISC Manual can also be used to predict the test results of the full-size specimens. To obtain an estimate of the ultimate load, the values given in Col. (3) of Table 3 should be divided by the term $0.50\phi = 0.45$. The result is listed in Col. (4) of the table and the per cent error of this prediction as compared to the test value is given in Col. (5). In this case, the estimate of the ultimate load is always made unconservatively. This occurs because the predicted ultimate strength of the basic weld is significantly greater than the measured weld coupon strength. The respective figures are 2.15 kN/mm and 1.71 kN/mm. The element of unconservatism here is not of any great consequence because it is the factored tensile resistance (Col. 3 of Table 3) that would be used for design purposes.

Rotation Behavior

The prediction of the ultimate strength of eccentrically loaded weld groups has not included any description of the rotation characteristics of the connection. Theoretically, this should be attainable from the analysis procedure but it has not been included in the work reported herein. The general characteristics of the load vs. rotation response are always of interest, however, and they are reported in Fig. 7.

Summary and Conclusions

Three full-size tests of eccentrically loaded fillet welded connections have been reported. In each case, the loading of the fillet weld arrangement was in-plane and horizontally-oriented fillet welds were used. Tests to establish the basic strength and deformation characteristics of the fillet welds used in the full-size pieces were also conducted.

The method developed by Butler, Pal and Kulak has been used to predict the ultimate load of the full-size test pieces. In each case, the predicted loads were less than the test loads, and the difference between the two values was within acceptable limits.

A comparison has also been made between test loads and those which would be predicted using tabulated coefficients given in the CISC Manual. As expected, there is a large margin between the predicted factored resistance and actual test loads. Using the Manual values to estimate the test loads underestimates the actual loads.

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Table 1

Weld Coupon Tests

(1) Coupon No.	(2) Total Weld Length mm	(3) Ave. Leg Size mm	(4) Ult. Strength (See Notes a,b) kN/mm	(5) Ultimate Deformation(c) mm
1	129.0	8.3	1.82	1.93
2	113.8	9.0	1.69	3.84
3	115.6	8.6	1.67	3.12
4	120.9	9.0	1.64	2.82
5	107.4	8.6	1.72	N.A.

Notes: a) The ultimate strengths given in Col. (4) are for a 6.35 mm (1/4 in.) fillet leg size.

b) The mean ultimate strength is 1.71 kN/mm

c) The mean ultimate deformation is 2.92 mm.

Table 2

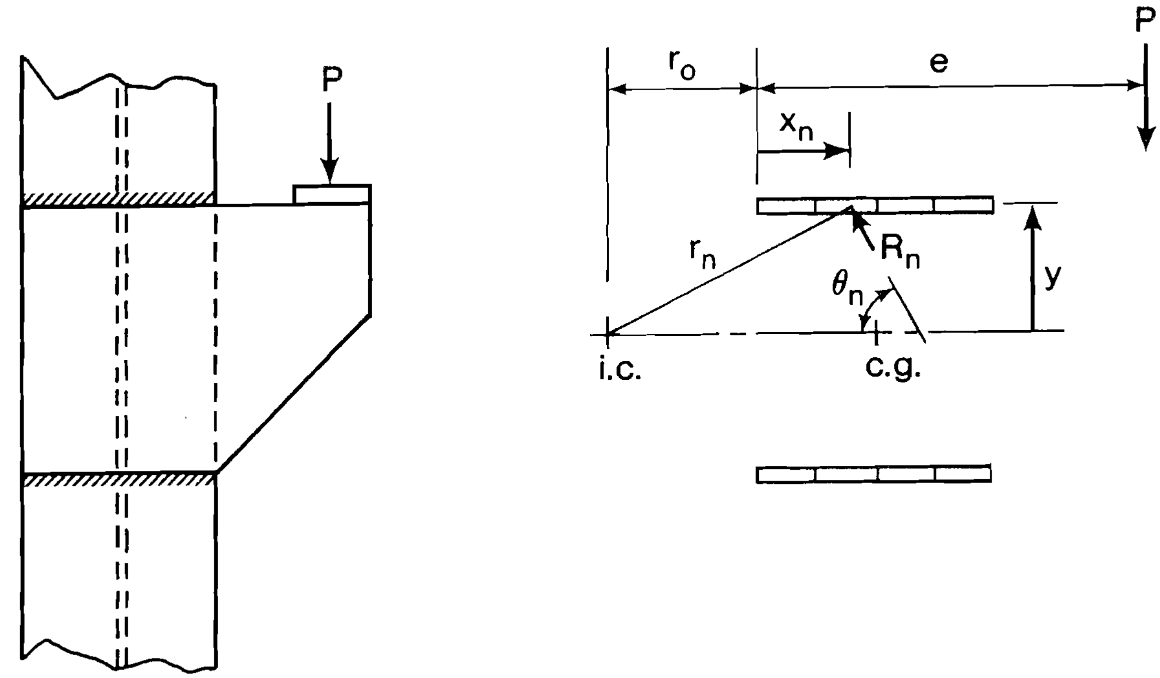
Summary of Full-Size Tests

(1)	(2)	(3)	(4)	(5)	(6)
Specimen No.	Weld Length mm	Leg Size mm	Test Load kN	Pred. Load kN	Per Cent Error
1	203.5	7.0	612.3	602.5	-1.6
2	199.6	7.2	464.9	439.8	-5.4
3	200.9	7.0	499.6	441.2	-11.7

Table 3

Predictions Made Using CISC Manual

(1)	(2)	(3)	(4)	(5)
Specimen No.	Test Load kN	Factored Resist. kN	Pred. Load kN	Per Cent Error
1	612.3	322	717	+17.1
2	464.9	212	471	+1.3
3	499.6	236	525	+5.1



Eccentrically Loaded Weld Group

Idealization

Fig. 1 Eccentrically Loaded Weld and Idealization

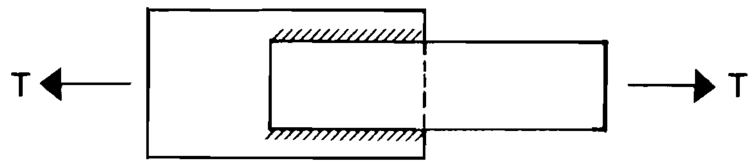


Fig. 2 Weld Coupon

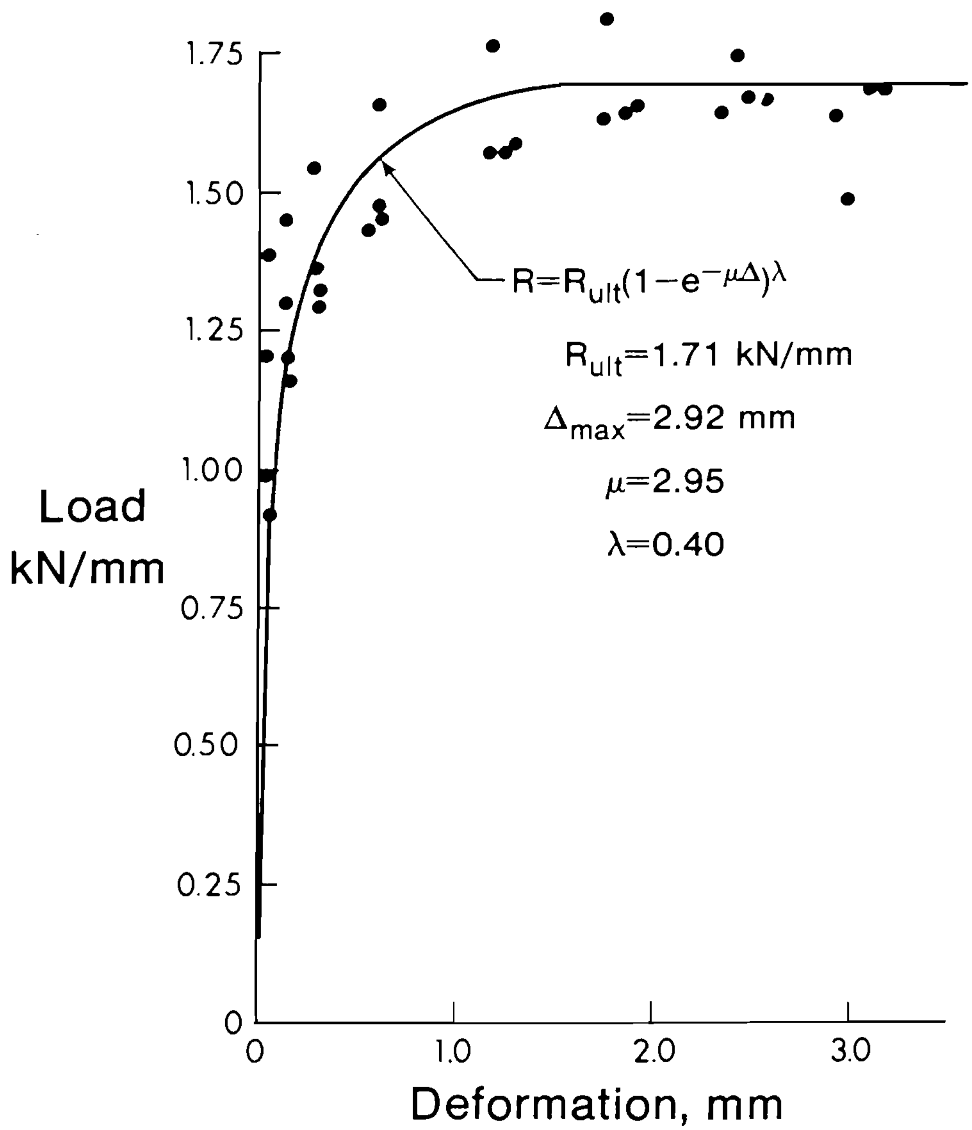


Fig. 3 Weld Coupon Test Results

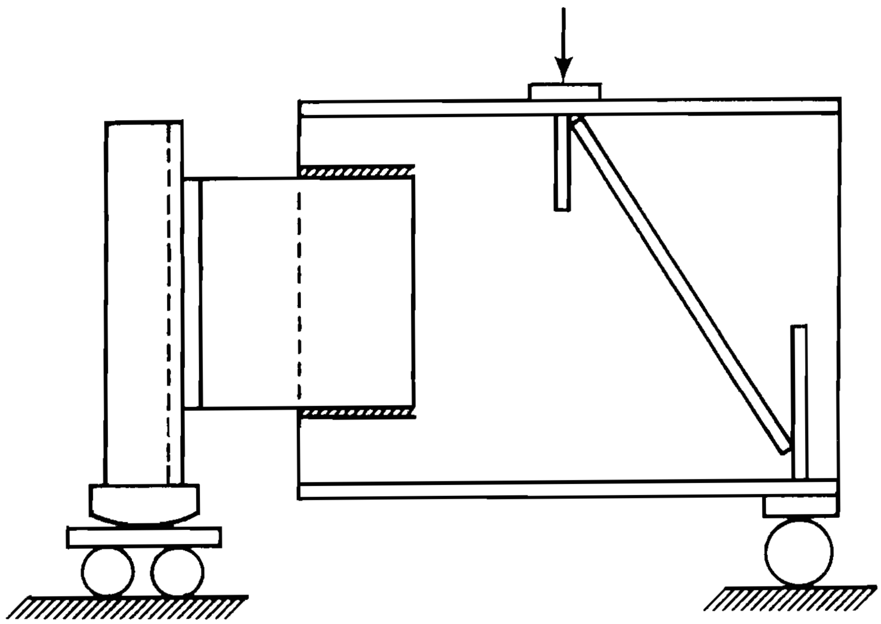


Fig. 4 Full-Size Test Piece

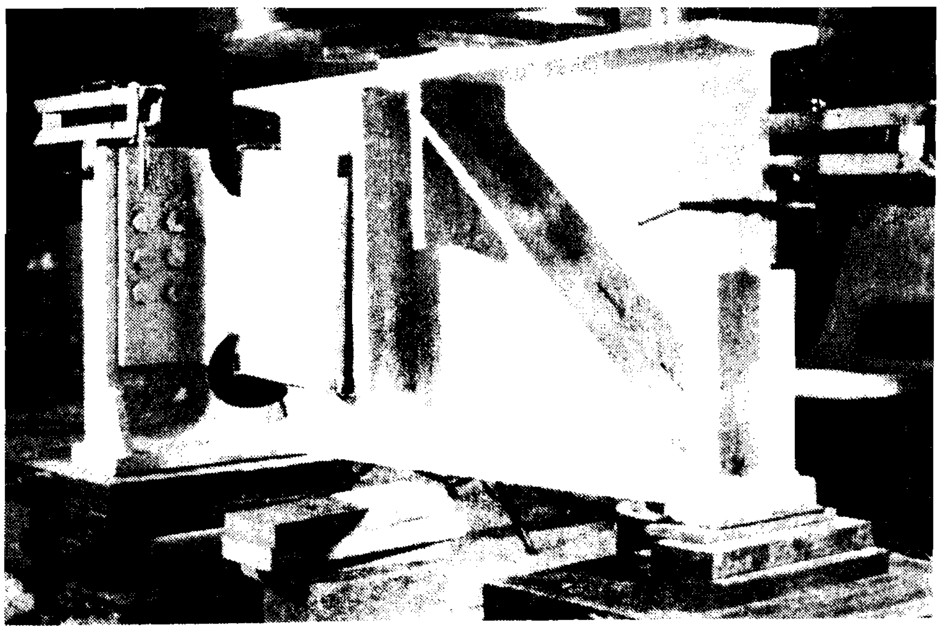
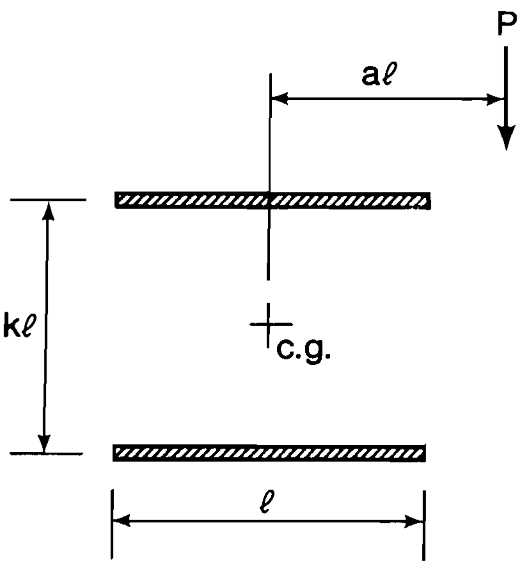


Fig. 5 View of Test Piece



Test No.	L mm	a	k
1.	200	0.7	1.0
2.	200	1.5	1.5
3.	200	2.0	2.0

Fig. 6 Summary of Geometry, Full-Size Specimens

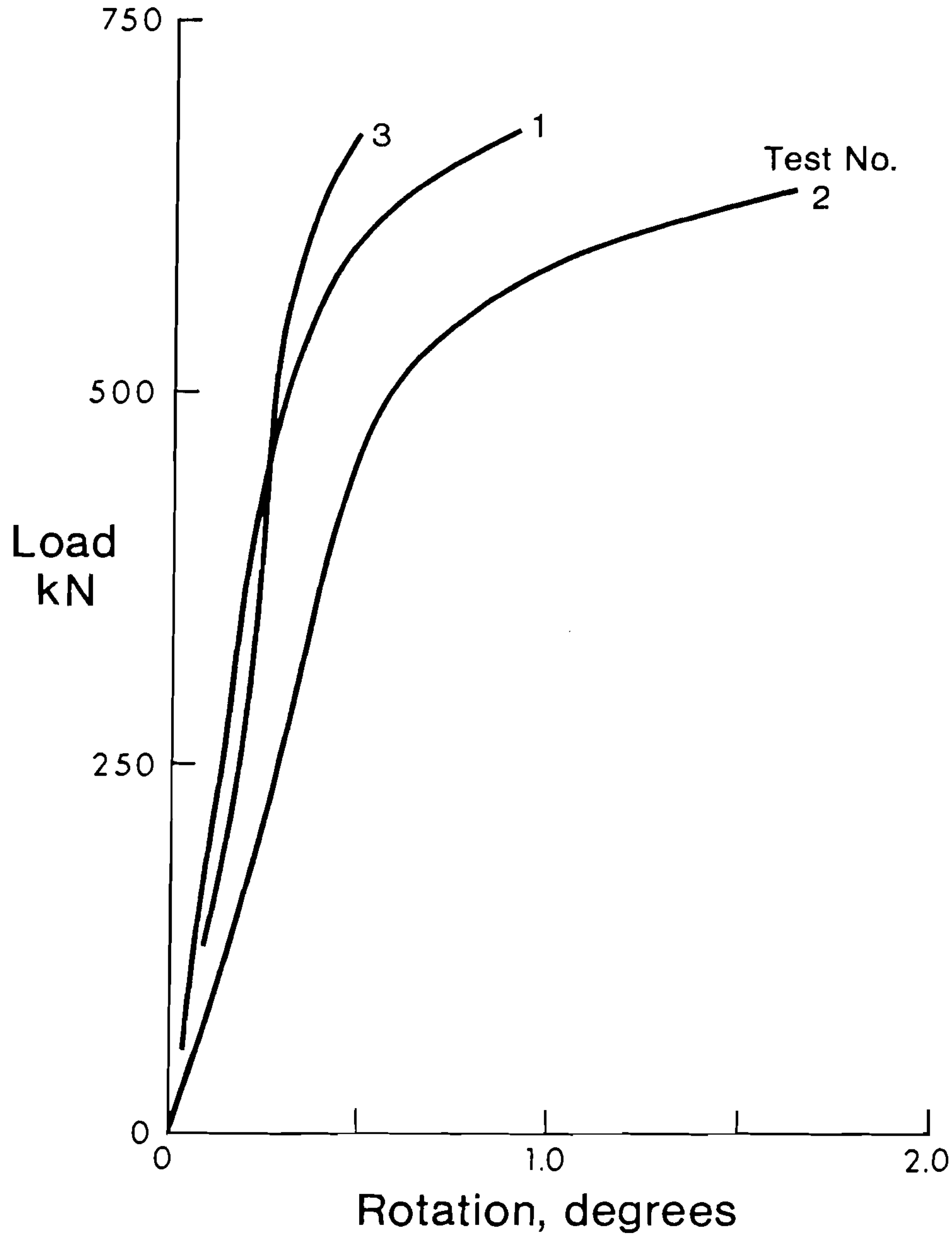


Fig. 7 Load vs. Rotation Response of Full-Size Specimens

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