AN EXPERIMENTAL STUDY OF THE EFFECTS OF NOTCHING ON THE STRENGTH OF STEEL

Thesis for the Degree of B. S.

MICHIGAN STATE COLLEGE

William E. Cranmer

1949

An Experimental Study of the Effects of Notching on the Strength of Steel

A Thesis Submitted to
The Faculty of
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of
AGRICULTURE AND APPLIED SCIENCE

by

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Candidate for the Degree of
Bachelor of Science

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He also wishes to extend his gratitude to Professor L. V. Nothstine for his advise, encouragement, and splendid photographic work.

CONTENTS

INTRODUCTION

The first bridge was probably a log thrown across a stream. A furthur development of this was the use of two logs with cross sticks upon them to form a floor. When greater spans were needed the truss was developed and perfected. It was not until 1847 that the stresses in trusses were fully analyzed, although trusses were constructed according to the judgement of the builder before this date.

In 1847 Squire Whipple issued a book upon bridge building, and he was the first to correctly analyze the stresses in a truss, Soon afterwards, the solution of stresses became very generally understood, wooden trusses were discarded for iron ones, and still later, steel replaced iron as a bridge-truss material. From this time, the development of bridge building was very rapid. Today we have structual giants that span hundreds of feet of water and tower over the largest cities.

There are a great many minor structual failures but unless there is loss of life or other newsworthy features about the failure, it never comes to the attention of anyone except the firm that repairs the damage. Many failures are caused by improper details. It has been a habit of "handbook engineers" to select members of ample size and then to connect them inadequately. Undoubtedly, this is due tothe fact that member selection is often quite simple while joint design requires a great understanding of the problem.

It is no secret that structual steel is handled rather roughly in the shop and in the field, Rivet holes seldom line up perfectly and they must be pulled into line. Welding warps and buckles the structure and leaves high residual stresses. During fabrication, bent shapes are straightened as a standard part of the fabrication process. The mere punching of a hole distorts the surrounding material and leaves high residual stresses. These processes will result in a structure having "stress risers", such as notches, holes, threads, and cross-sectional changes. Such a structure would be highly unsafe if it were not constructed of a ductile material such as structual steel. When a minute flaw in the material coincides with the location of a point of high residual stress, a failure is likely to result. Failures have often been traced to such influences.

In all the connections of a truss there are certain stress risers. It is the purpose of this thesis to study the effect that these notches have on the strength of steel.

DEFINITIONS

Stress is the interval resistance developed in a body when strained by the application of external forces.

Strain is the distortion or change in shape of a body produced by the application of equal but opposite forces, and is measured in units of length.

Elasticity is that property which a material possesses of returning to its original form and dimensions when the external forces causing distortion are removed.

The Proportional limit is the greatest stress which a material is capable of developing without deviating from the law of proportionality of stress to strain.

The Elastic limit is the greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of the stress.

Yield Strength is a measure of the maximum ulitizable strength of the material and is taken as .2 per cent of the permanent set.

Yield Point is the load at which the specimen elongates considerably without an increase in load.

Ultimate Strength is the maximum stress reached before breaking the specimen.

These definitions can be divided into two classes: first, those dealing with the elastic properties of the material, and second, those dealing with the non-elastic or ductile properties. On the first depend entirely the possibility of structure withstanding the design loads without permanent set occuring and on the second depends the possibility of their being able to carry, in emergency, local stresses in excess of those pertaining to elastic conditions.

STRESS DETERMINATION AND DISTRIBUTION

The determination and distribution of stresses in a structure are of prime importance to the engineer. There are an immense variety of problems that arise from what seem to be a comparatively simple problem. The problem is not only one of determination and distribution of stress but also of the engineering significance of the stresses and strains under various conditions of loading. The usable strength of a member does not depend alone on the value of the maximum stresses and strains but also what adjustment these members can make in meeting the conditions different from those assumed in design. The extent to which these adjustments can be made will depend on the properties of the material such as elasticity and ductility, on the relative volume of the member, on the method of loading.

There are, in general, two ways of determining the stresses and strains in a member: (1) by mathematical analysis and (2) by experimental means, in which case the actual member may be used as in the strain-gage method.

The method of obtaining the stress at a section of a member is to assume that the stresses are distributed according to a definite mathematical law. The assumption is made that there are no abrupt changes in the law of elastic behavior throughout the member. Four general conditions must exist for this assumption to be true. (1) The material must be continuous. (2) The properties of the material must not change from point to point. (3) The cross-section shall be constant and there shall be no abrupt change. (4) The material considered must not be near the point at which the external force is applied.

The assumption that there is a definite law of distribution of stress in a member is probably never realized. This is due to the fact that the material is not entirely continuous and capable of being subdivided indefinitely without losing any property that it has when in a large piece. Steel and other metals are made up of crystalline grains whose properties vary and whose random arrangement greatly influences the stress distribution throughout the member. This is illustrated in figure 1. The formula assume that the stress is evenly distributed. While the colored line shows the probable distribution of stress.

So far, the discussion has been about bars of a prismatical form. Then, for centrally applied loads, the stress at some distance from the end is nearly uniformly distributed over the cross-section. Abrupt changes in cross-section give rise to great irregularities in stress distribution. These stress concentrations are represented in figure 2 by colored line.

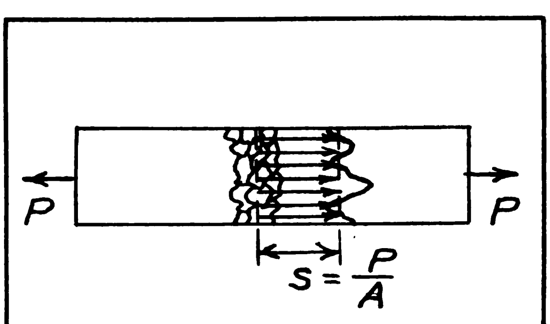


figure 1

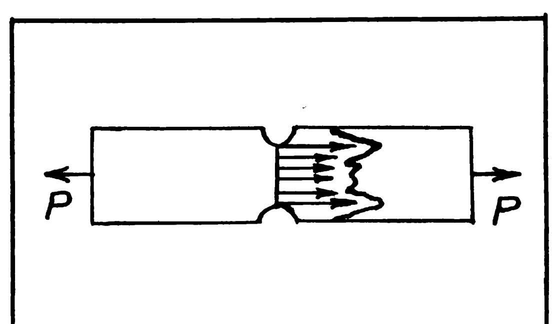


figure 2

WORKING STRESSES

The selection of working stresses is of the utmost importance to the engineer, and if the design is to be sound, it is essential that we have very clear ideas regarding them. If this factor is taken too high the structure may prove weak in service. On the other hand, if the working stresses are too low, the structure becomes unnecessarily heavy and uneconomical. In the case of ductile materials, such as structural steel, it seems logical to take the yield point as the basis for determining working stresses because of considerable deformation which takes place at the yield point are seldom permissible in engineering structures.

THE SPECIMENS

Static tension tests are the most common type of test and are the most useful in revealing the true character of the material. This type of test closely resembles the load that is put on a structure where the effects of impact as neglegiable.

The steel used in the test was a mild 20 carbon steel. This type of steel is commonly used in structual work.

All the test bars were cut form the same piece of steel which was slightly over 15 feet in length and whose nominal dimensions were 2 inches by ½ inch.

The first bar to be made was the control bar (1A). This bar was made so that there would be no stress concentrations. This bar would act as if it had a continuous cross-section dimension of 0.433 X 1.383.

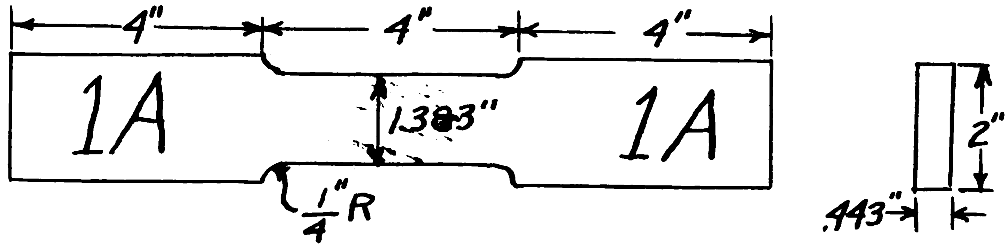
Bar 2A has a square cut notch, bar 3A has a hack saw cut, and bar 4A has a V notch.

Bar 5A represents any one of the above three severe notched bars that has been hollowed out.

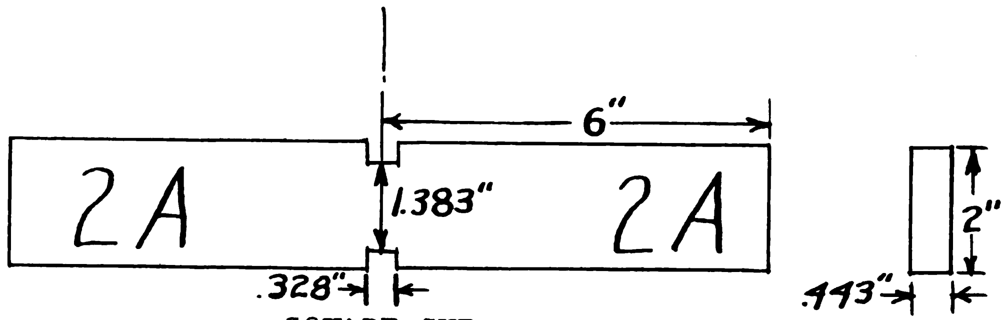
It should be noted that the least cross-sectional dimentions of all the bars are the same.

Originally there were two specimens made of each type, after testing these ten bars it was necessary to make three more to obtain more data for the conclusions.

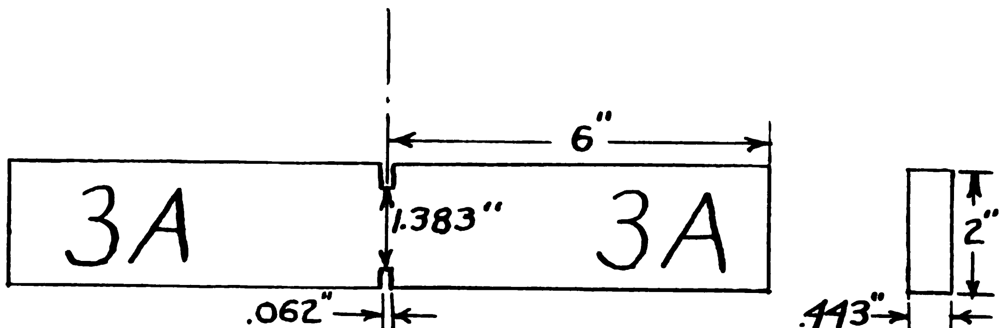
The numbers on each bar note a type of notch and the letters note the number of bars made of this type.



CONTROL

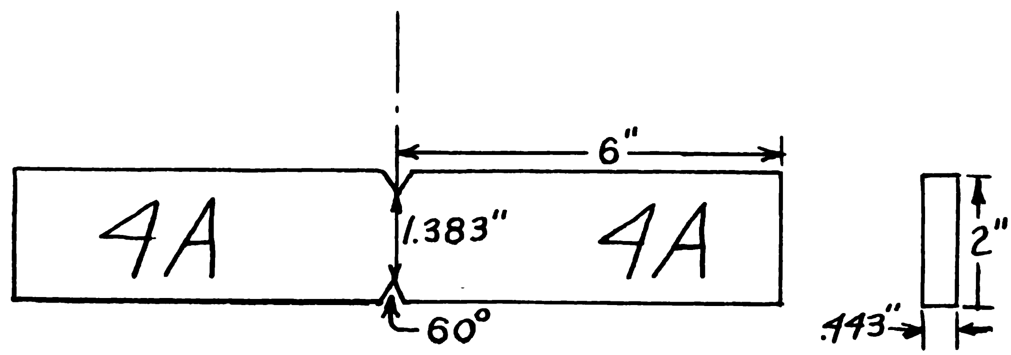


SQUARE-CUT

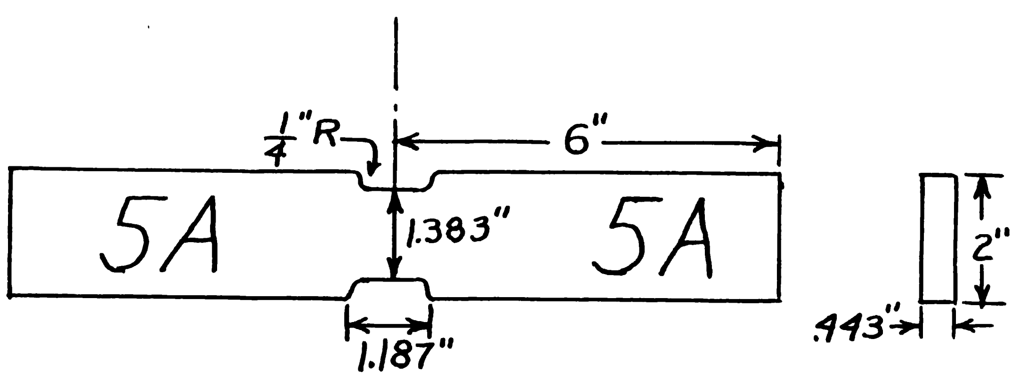


HACK SAW CUT

BAR DIMENSIONS



V-NOTCH



HOLLOWED OUT NOTCH

BAR DIMENSIONS

THE TESTS

Purpose

1. To determine the effect that notching has on the strength of ductile steel when it is statically loaded.
2. To find where the stress is concentrated.
3. To determine the safe use of notched ductile material.

Specimen

1. Commercial type, having a 2 inch gage length and cut to specifications.

Test Machine

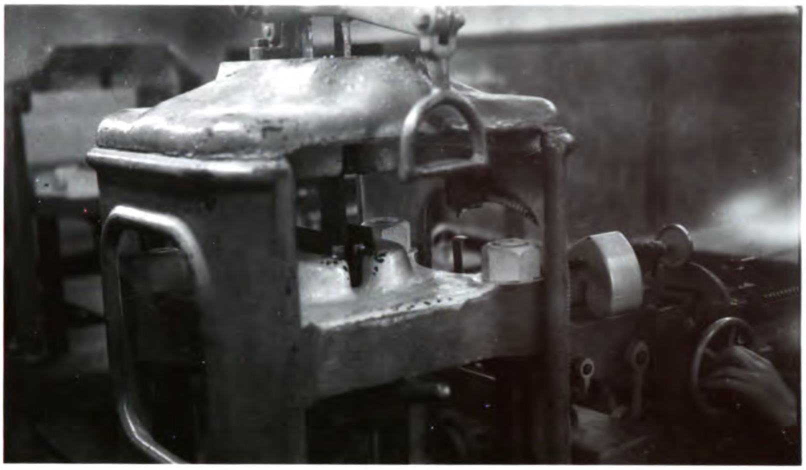
All the tests were run on a Riehle universal testing machine. The set up of the specimen can be seen in the photographs. The speed of the cross head was 0.0558 inches per minute.

Procedure

1. Punch mark a 2 inch gage length on the specimen with the notch half way between the two punches.
2. Place the specimen in the holders so that it is gripped evenly by the jaws. Take up the slack in the system by moving the cross head down and placing an initial load of 2,000 lbs.
3. Set the strain gage in place and clamp firmly. Zero the strain gage after the initial load is applied.
4. Record the gage reading and load to the elastic limit. Then remove the gage and load until complete failure. Apply the load uniformly.

REMARKS

There was a slight discrepency between bars 3A and 3B so bars 3C and 3D were made to find out more about the strength of the specimen. It was then noted that bars 3B, 3C, and 3D tested about the same so the results of 3A were believed to be inaccurate. Bar 1C was made because there were not many points obtained for plotting a reliable gage-load curve. Due to lack of time, bar 1C was made rather hurriedly and so the accuracy of the results are questionable. All the other bars tested rather well as can be seen by comparing the curves of each type of notched bar.



The test specimen in place

Putting on the strain gage

Adjusting the strain gage

MLIT-232

Sheet No. 1

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension Test of Specimens 1A & 1B

Observers { P. De Koning / W. E Cranmer

Date April 27, 1949

No.	1A	Load in thousands of pounds	Gage Reading "/1000			1B	Load thousands of pounds	Gage Reading "/1000			
1		2	0.0				2	0.0			
2		5	2.2				5	1.3			
3		10					8	3.0			
4		15	5.1				10	4.1			
5		20	8.2				12	5.0			
6							14	6.0			
7		35,320# ultimate strength					16	7.0			
8							18	8.0			
9							20	9.1			
10							22	10.0			
11							24	11.0			
12							25	108.8			
13											
14							35,230# ultimate strength				
15											
16											
17											
18											
19											
20											
21											
22											
23											
24											
25											

Remarks: Initial load of 2,000#
Gage ratio 10 to 1
[illegible]

MLIT-232

Sheet No. 2

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension test of Specimen 1C

Observers: W. E. Cranmer

Date May 10, 1949

No.	1C	Load in thousands of pounds	Gage Reading 1/1000
1		2	0.0
2		5	0.7
3		8	2.1
4		10	3.0
5		12	4.0
6		14	5.0
7		16	6.4
8		18	9.1
9		19	12.0
10		20	14.2
11		21	20.0
12		22	29.0
13		23	
14			
15		33,960# ultimate	
16		strength	
17			
18			
19			
20			
21			
22			
23			
24			
25			

Remarks: Initial load of 2000#
Gage ratio 10 to 1

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Sheet No. 3

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension test of Specimens 3A, & 3B

Observers: W. E. Cranmer

Date April 27, 1949

No.	2A Load in thousands of pounds	2A Gage Reading 1/1000"			3B Load thousands of pounds	3B Gage Reading 1/1000"	
1	2	0.0			2	0.0	
2	5	1.0			5	0.8	
3	8	2.2			8	2.0	
4	10	3.0			10	2.8	
5	12	3.8			12	3.6	
6	14	4.6			14	4.5	
7	16	5.5			16	5.2	
8	18	6.5			18	6.4	
9	20	7.5			20	7.0	
10	21	8.1			21	7.5	
11	22	10.0			22	8.0	
12	23	11.8			23	8.8	
13	24	15.8			24	18.8	
14	25	68.0			24.5	47.5	
15	25.5	80.0			25	56.0	
16	26	99.0			25.5	67.5	
17							
18	38,240#		ultimate		38,450#		ultimate
19			strength				strength
20							
21							
22							
23							
24							
25							

Remarks: Initial load of 2000#
Gage ratio 10 to 1

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Sheet No. 4

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension Test of Specimens 3A & 3B

Observers: W.E. Crammer, J. Brennan

Date April 27, 1949

No.	3A Load in thousands of pounds	3A Gage Reading 1/1000"	3B Load in thousands of pounds	3B Gage Reading 1/1000"
1	2	0.0	2	0.0
2	5	0.8	5	0.8
3	8	1.8	8	1.8
4	10	2.4	10	2.4
5	12	3.3	12	3.1
6	14	4.0	14	4.0
7	16	5.0	16	5.1
8	18	5.8	18	6.9
9	20	6.8	20	10.0
10	21	7.1	21	12.0
11	22	7.8	22	16.0
12	23	8.3	23	19.0
13	24	9.4	24	22.6
14	25	18.8	25	29.0
15	25.5	40.4	25.5	36.8
16	26	52.0	26	46.5
17	26.5	64.0	26.5	56.8
18	27	74.0	27	73.0
19	27.5	87.5	27.5	84.0
20				
21	38,385 # ultimate strength		38,130 # ultimate strength	
22				
23				
24				
25				

Remarks: Initial load of 2,000 #
Gage ratio 10 to 1

MLIT-232

Sheet No. 5 19.

MECHANICAL ENGINEERING LABORATORY
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Running Log of Tension Test of Specimens 3C & 3D

Observers: W.E. Cranmer

Date May 10, 1949

No.	3C	Load in thousands of pounds	Gage Reading 1/1000"			3D	Load in thousands of pounds	Gage Reading 1/1000"			
1		2	0.0				2	0.0			
2		5	0.8				5	1.0			
3		8	2.0				8	2.5			
4		10	3.0				10	3.2			
5		12	3.9				12	4.1			
6		14	4.9				14	5.0			
7		16	5.8				16	6.0			
8		18	7.5				18	7.1			
9		19	10.0				19	8.0			
10		20	12.0				20	9.1			
11		21	16.0				21	11.0			
12		22	20.0				22	14.0			
13		23	24.0				23	17.5			
14		24	32.0				24	23.0			
15		25	46.0				25	29.0			
16		26	68.0				26	49.0			
17											
18		38,080 #		ultimate			38,360 #			ultimate	
19				strength						strength.	
20											
21											
22											
23											
24											
25											

Remarks: Initial load of 2,000 #
Gage ratio 10 to 1

20.

MLIT-232 Sheet No. 6

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension Test of Specimens 4A & 4B

Observers: W. E. Cranmer

Date April 22, 1949

No.	4A	Load in thousands of pounds	Gage Reading 1/1000"			4B	Load in thousands of pounds	Gage Reading 1/1000"				
1		2	0.0				2	0.0				
2		5	1.0				5	0.8				
3		8	2.0				8	1.8				
4		10	3.0				10	2.6				
5		12	3.5				12	3.2				
6		14	4.3				14	4.1				
7		16	5.3				16	5.0				
8		18	5.9				18	6.0				
9		20	6.9				20	6.6				
10		21	7.2				22	7.3				
11		22	7.8				24	8.1				
12		23	8.2				25	9.0				
13		24	8.5				26	9.9				
14		25	9.0				26.5	20.0				
15		26	9.9				27	67.0				
16		27	23.0				27.5	87.0				
17		27.5	74.0									
18		28	95.0				38,550 ultimate strength					
19												
20		38,840# ultimate strength										
21												
22												
23												
24												
25												

Remarks: Initial load of 2,000#
Gage ratio of 10 to 1

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Sheet No. 1

MECHANICAL ENGINEERING LABORATORY
MICHIGAN STATE COLLEGE

Running Log of Tension Test of Specimens 5A & 5B

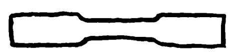
Observers: W. E. Cranmer

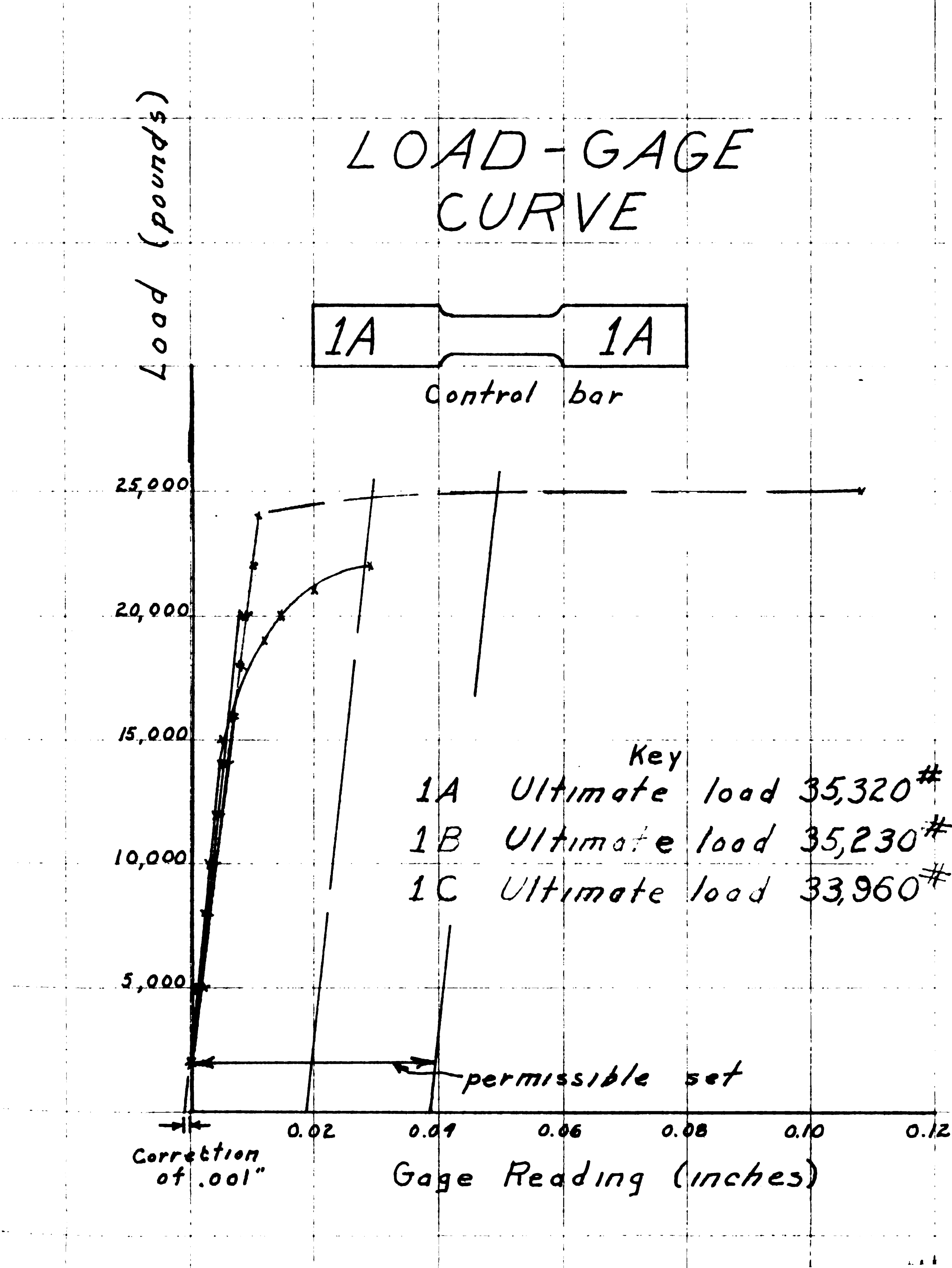
Date April 27, 1949

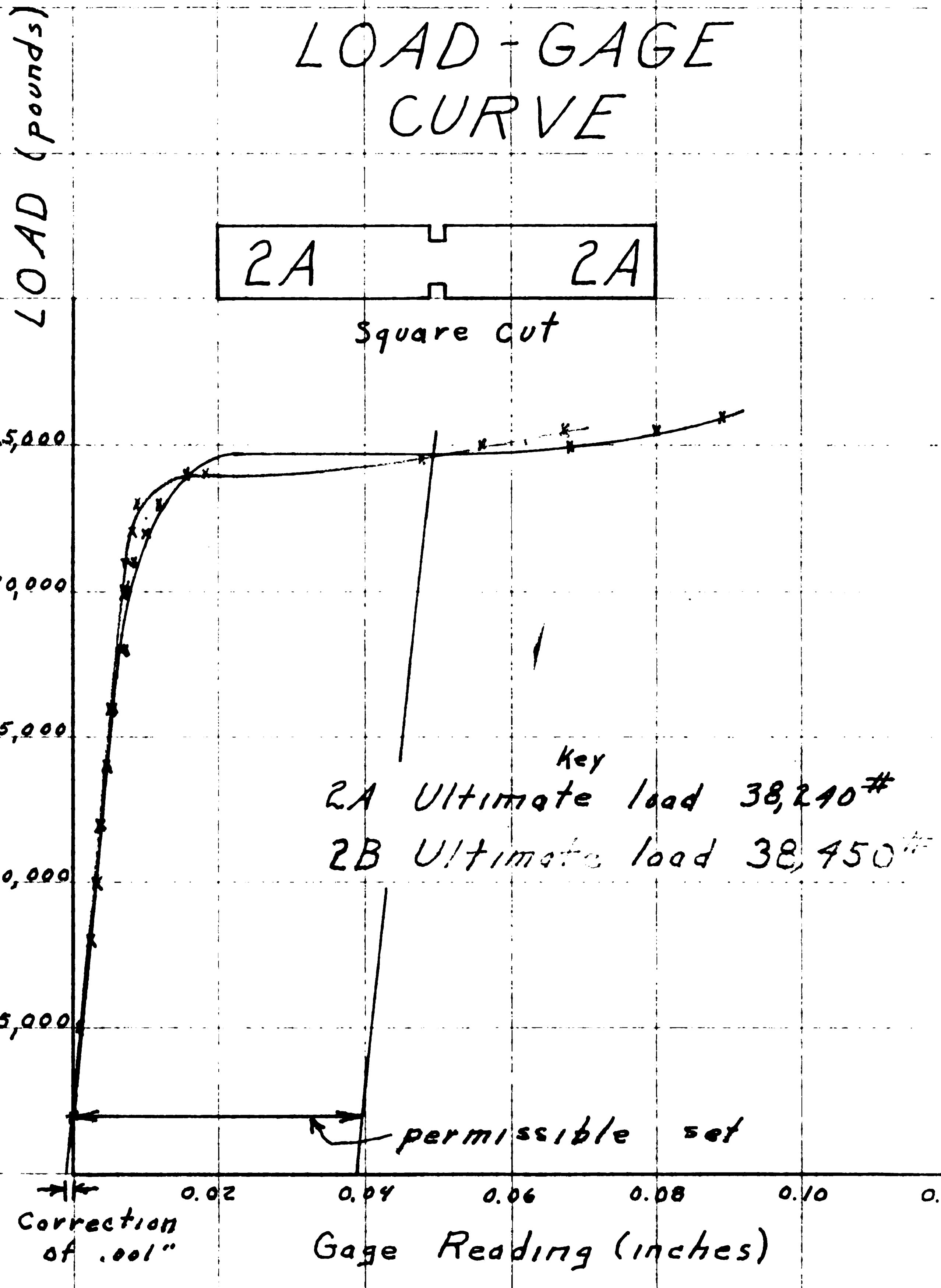
No.	5A	Load in thousands of pounds	Gage Reading 1/1000"			5B	Load in thousands of pounds	Gage Reading 1/1000"			
1		2	0.0				2	0.0			
2		5	0.0				5	0.0			
3		8	0.9				8	0.8			
4		10	1.7				10	1.5			
5		12	2.2				12	2.0			
6		14	3.0				14	3.0			
7		16	4.0				16	4.0			
8		18	5.0				18	5.0			
9		20	5.7				20	6.3			
10		22	6.5				22	10.5			
11		24	31.0				22.5	12.5			
12		24.5	82.0				23	17.0			
13		25	106.0				23.5	34.0			
14							24	68.0			
15		37,520 #		ultimate			24.5	83.0			
16				strength			25	102.0			
17											
18							37,160 #		ultimate		
19									strength		
20											
21											
22											
23											
24											
25											

Remarks: Initial load of 2,000#

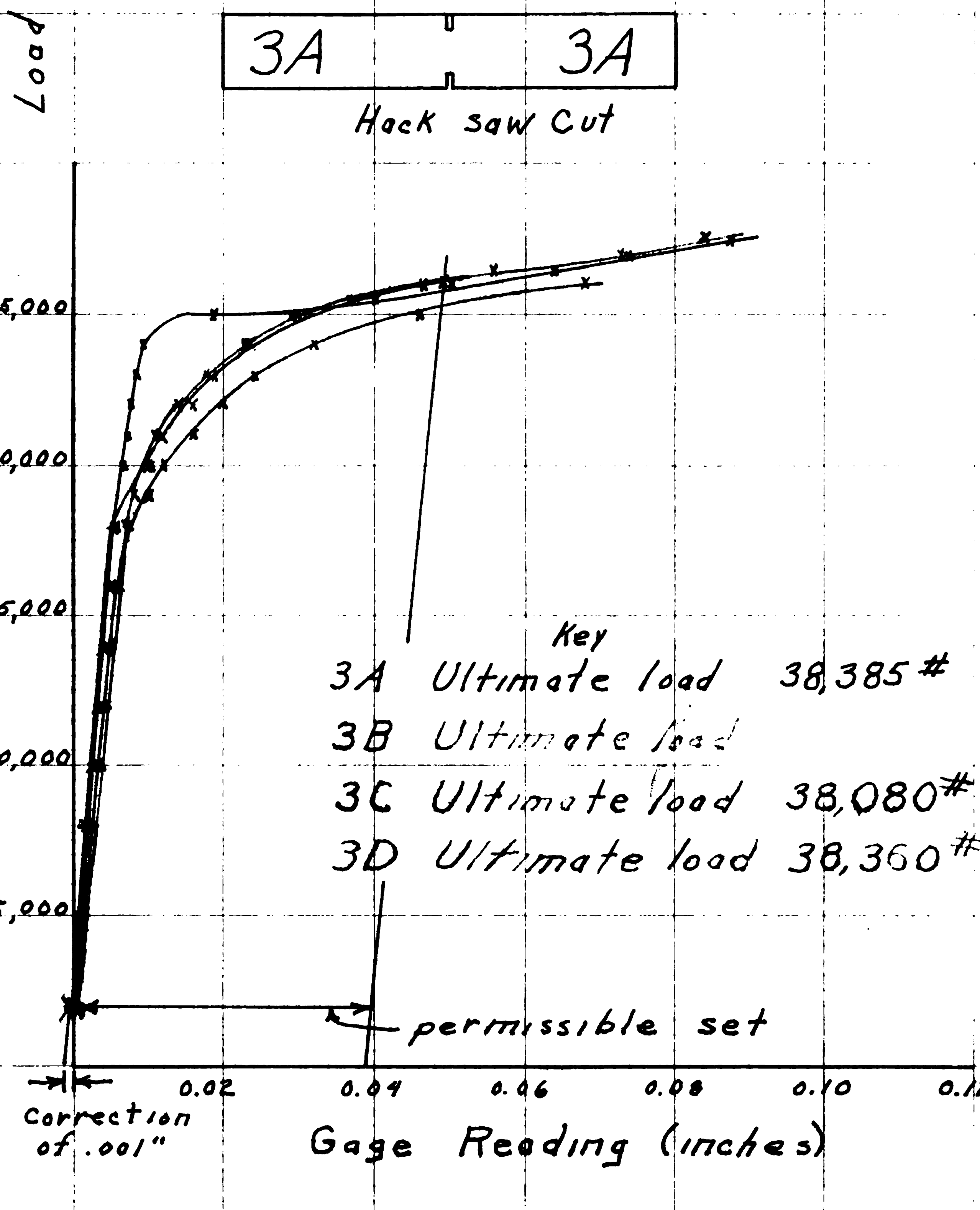
Gage ratio 10 to 1

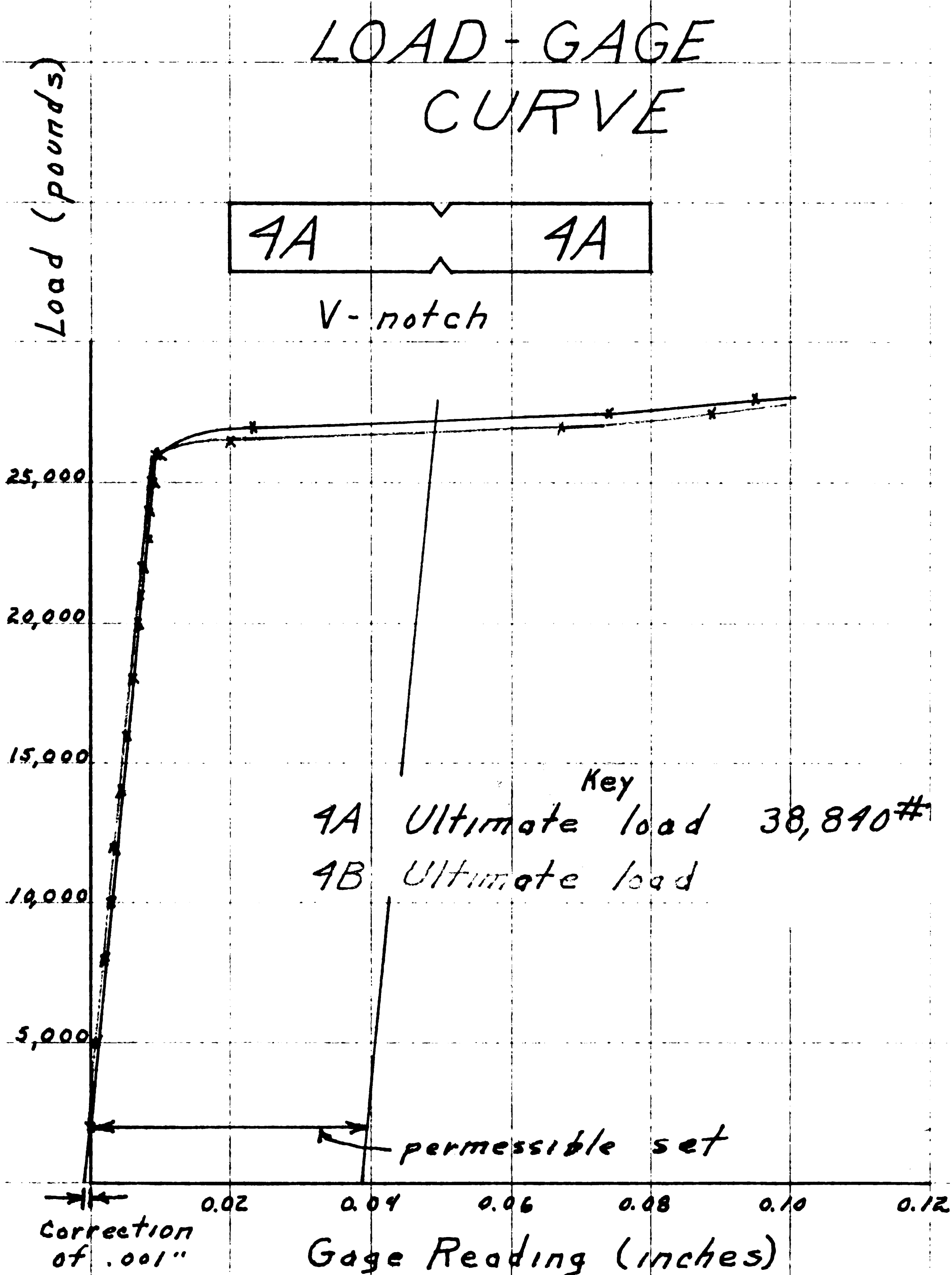
Member	SHAPE	ULTIMATE LOAD #	PROPOR-TIONAL LOAD #	YIELD POINT LOAD #	YIELD STRENGTH at .2% offset #	Length of yield distribution to 1/8"	ELONGATION to 1/64"	AREA after failure □"	REMARKS
1A	 CONTROL	35,320	20,000 +	20-25,000	----	2 +	2 60/64	.236	
1B		35,230	24,000	24-25,000	24,750	2 +	2 60/64	.248	
1C		33,960	16,000	21,500	21,500	2 +	2 60/64	.238	Seems Unreliable
2A	 SQUARE-CUT	38,240	20,000	25,000	24,900	1 4/8	2 30/64	.354	
2B		38,450	22,000	24,250	24,600	1 4/8	2 30/64	.342	
3A	 HACK SAW CUT	38,385	17,000	25,000	26,000	1 2/8	2 22/64	.468	Seems Unreliable
3B		38,130	16,000	26,000	26,000	1 2/8	2 22/64	.443	
3C		38,080	16,000	26,000	25,250	1 2/8	2 22/64	.426	
3D		38,360	16,000	26,000	26,000	1 2/8	2 22/64	.412	
4A	 V-NOTCH	38,840	26,000	27,000	27,000	1 3/8	2 22/64	.441	
4B		38,550	26,000	27,000	27,000	1 3/8	2 22/64	.432	
5A	 HOLLOWED OUT	37,520	22,000	24,000	24,000	1 6/8	2 36/64	.287	
5B		37,160	20,000	23,000	24,000	1 6/8	2 36/64	.298	

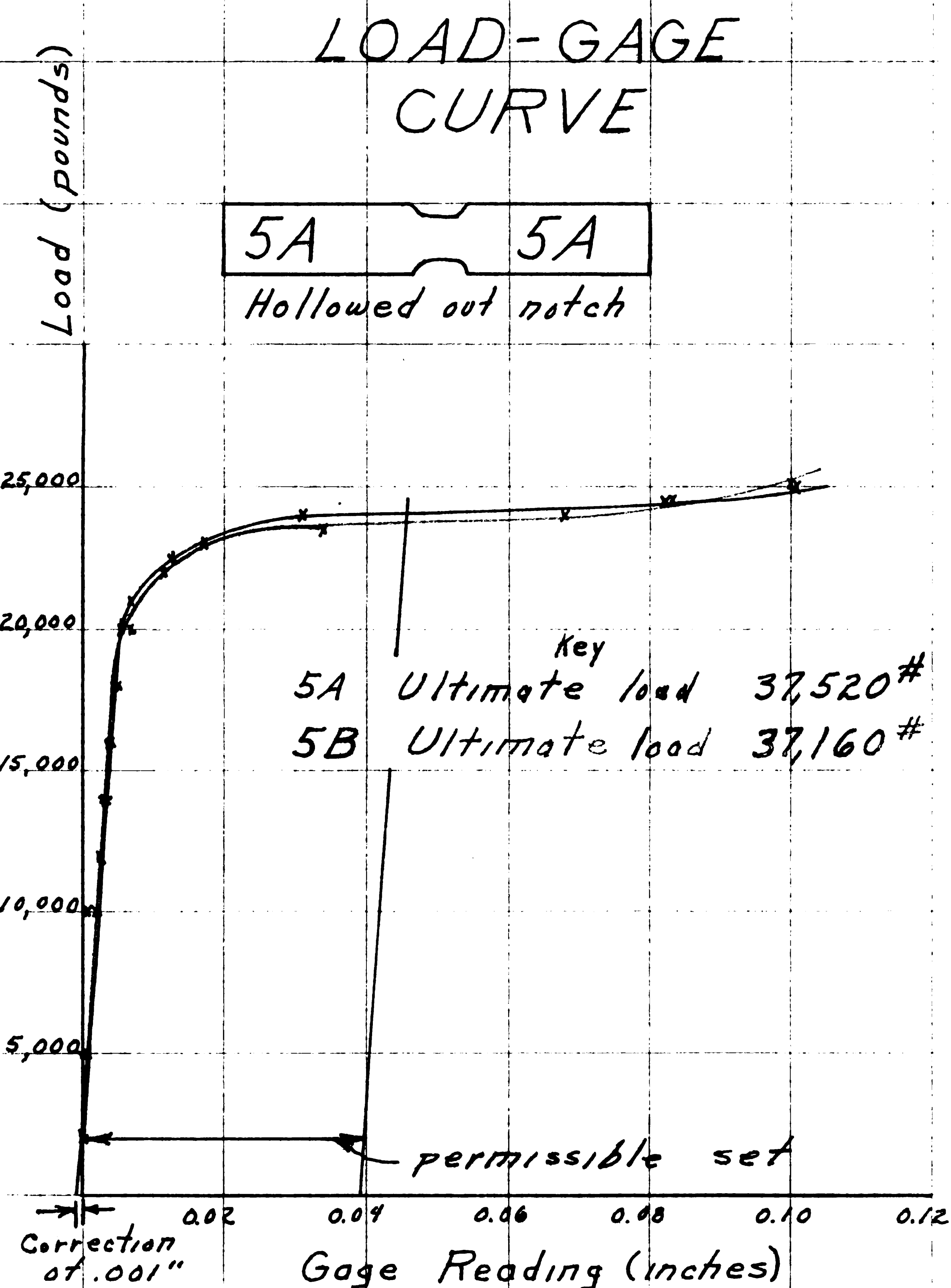

LOAD-GAGE CURVE
1A
1A
Control bar
Load (pounds)
25,000
20,000
15,000
10,000
5,000
Key
1A Ultimate load 35,320#
1B Ultimate load 35,230#
1C Ultimate load 33,960#
permissible set
Correction of .001"
0.02
0.04
0.06
0.08
0.10
0.12
Gage Reading (inches)

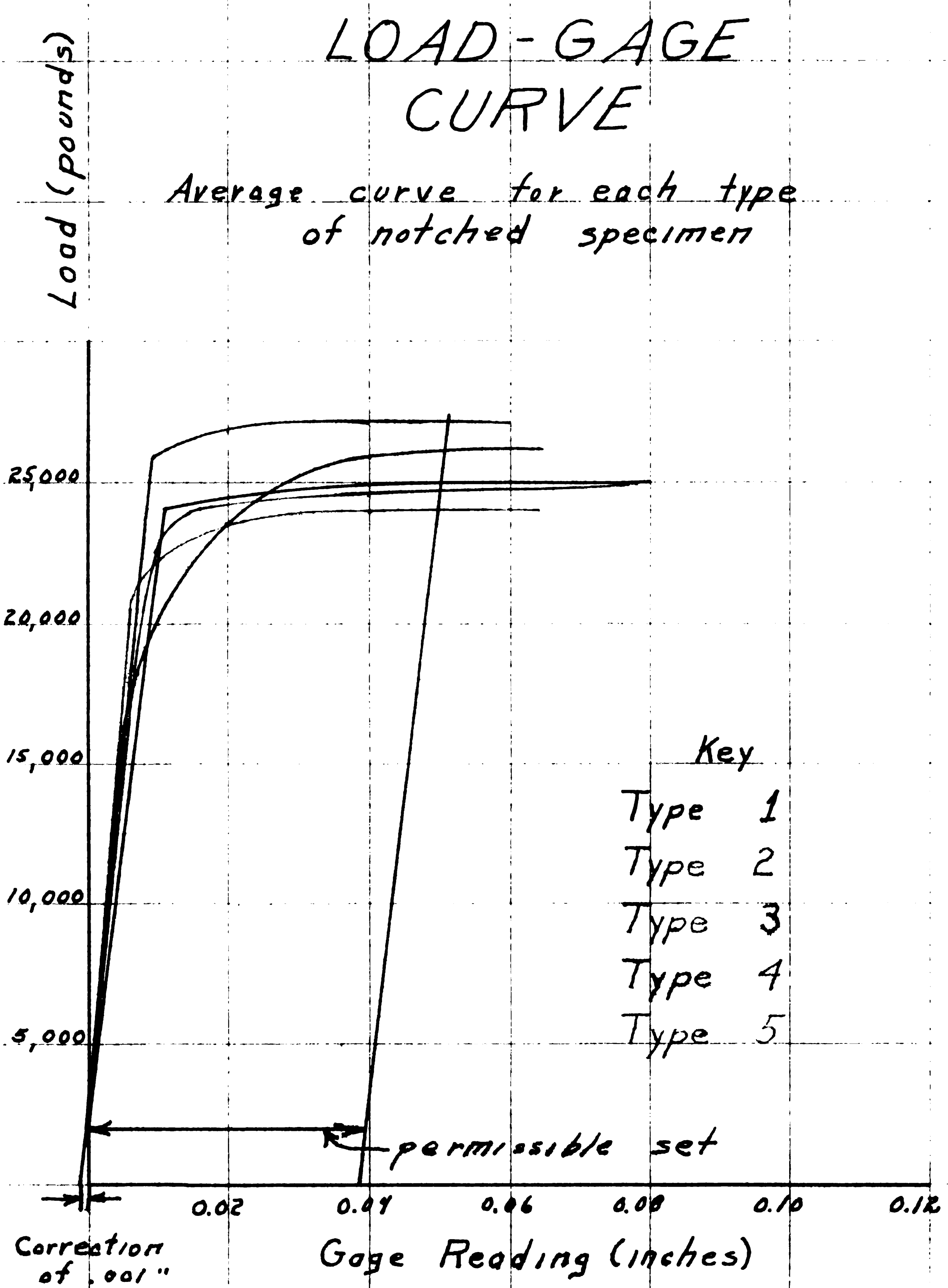

LOAD-GAGE CURVE
2A
2A
Square cut
LOAD (pounds)
25,000
20,000
15,000
10,000
5,000
Key
2A Ultimate load 38,240#
2B Ultimate load 38,450#
permissible set
0.02
0.04
0.06
0.08
0.10
Correction of .001"
Gage Reading (inches)

LOAD-GAGE CURVE

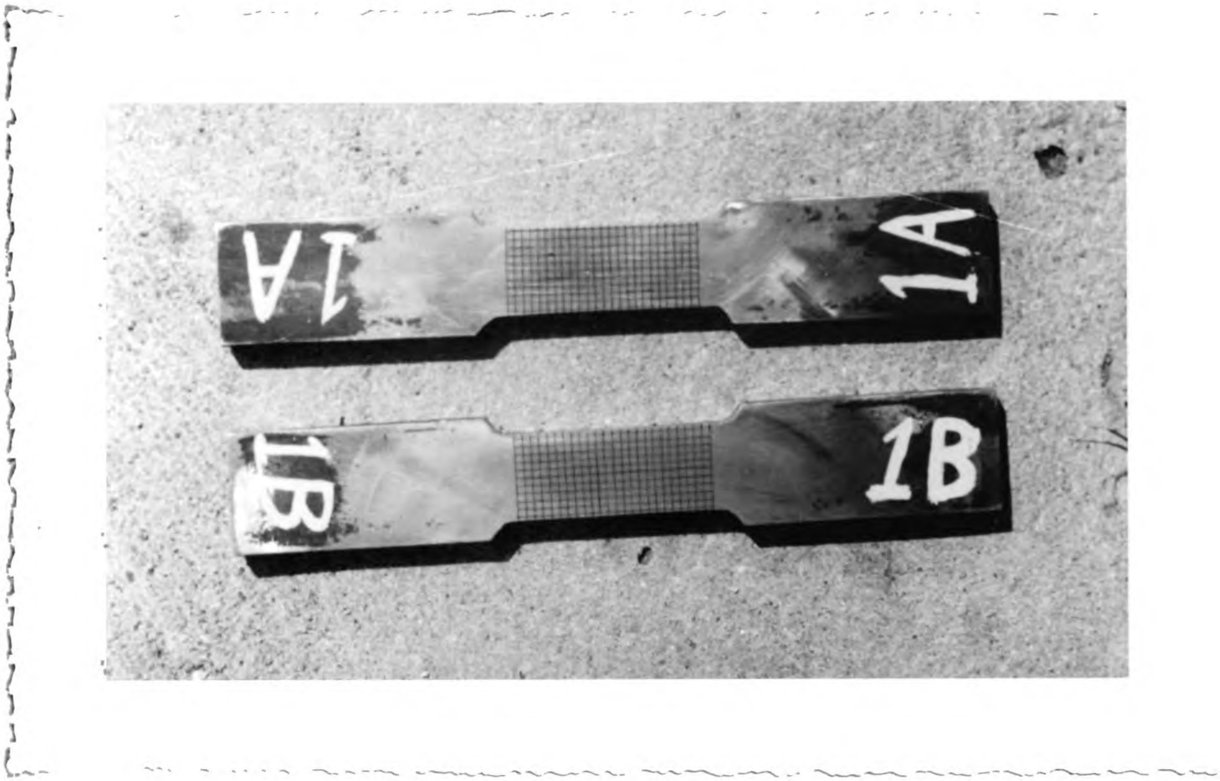



LOAD-GAGE CURVE
4A
4A
V-notch
Load (pounds)
25,000
20,000
15,000
10,000
5,000
Key
4A Ultimate load 38,840#
4B Ultimate load
permessible set
Correction of .001"
0.02
0.04
0.06
0.08
0.10
0.12
Gage Reading (inches)


LOAD-GAGE
CURVE
5A
5A
Hollowed out notch
Load (pounds)
25,000
20,000
15,000
10,000
5,000
Key
5A Ultimate load 37,520#
5B Ultimate load 37,160#
permissible set
Correction of .001"
0.02
0.04
0.06
0.08
0.10
0.12
Gage Reading (inches)


LOAD-GAGE CURVE
Average curve for each type of notched specimen
Load (pounds)
25,000
20,000
15,000
10,000
5,000
0.02
0.04
0.06
0.08
0.10
0.12
Gage Reading (inches)
Correction of .001"
permissible set
Key
Type 1
Type 2
Type 3
Type 4
Type 5

THE CONTROL



Before testing

After testing

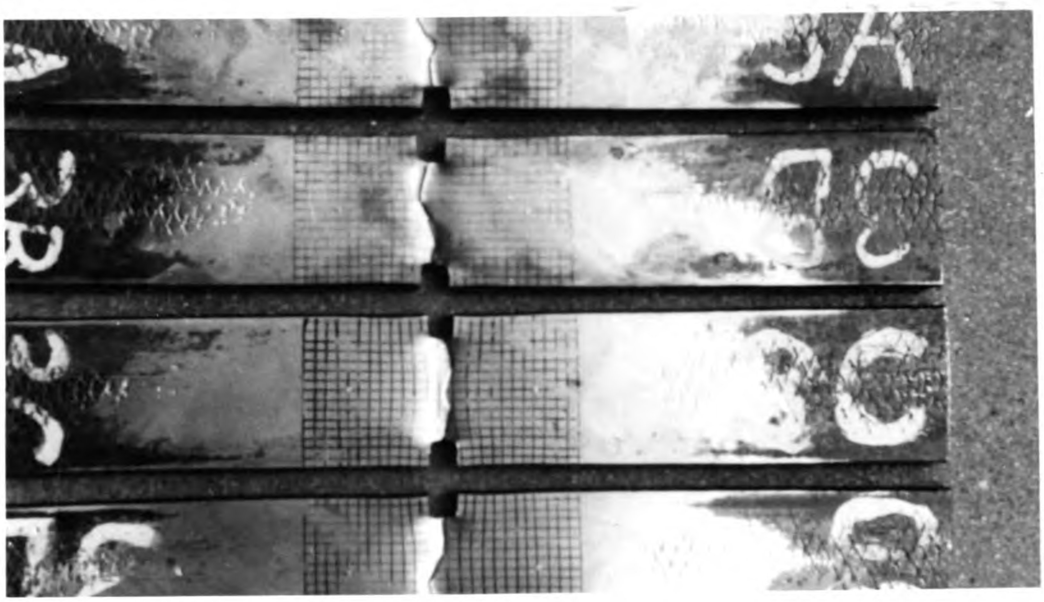
THE SQUARE CUT

Before testing

After testing

THE HACK SAW CUT

Before testing



After testing

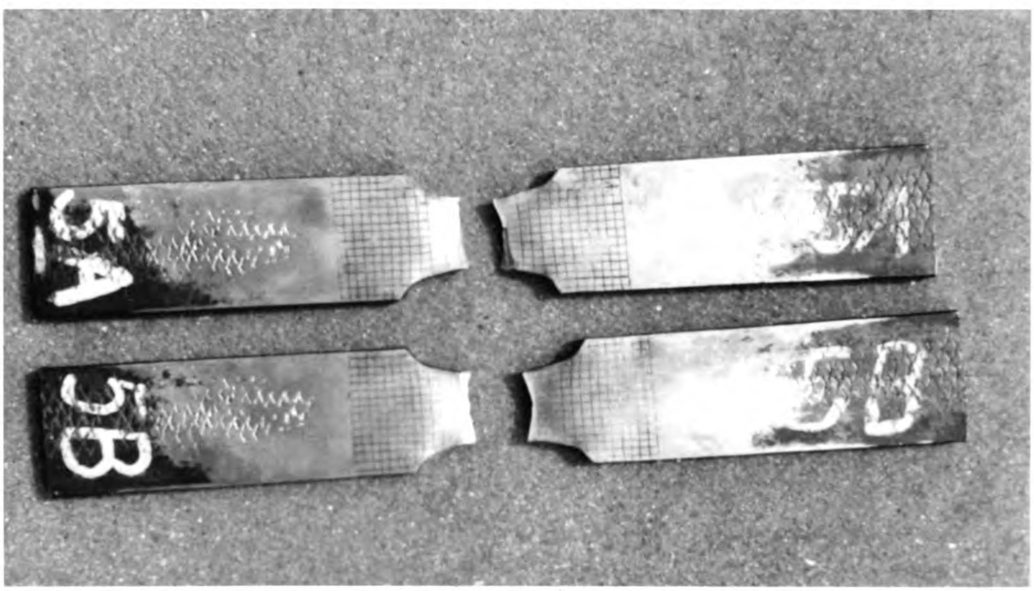
THE V-NOTCH

Before testing

After testing

THE HOLLOWED OUT NOTCH

Before testing



After testing

REMARKS ON HOW SPECIMENS BROKE

1A and 1B (The Control)

This was the control test section. It can be observed in the photographs that the lines curved outward so the yield was greatest in the middle of the section.

The yield was more evenly divided in this specimen than any other. This is true of the yield in both the horizontal and vertical directions. There was even noticable yield beyond the gage length.

The Riehle grips are swelled in the center sc as to grip the specimen hardest along its axis of symmetry. This gives the same type of loading as would be done in a riveted construction.

2A and 2B (The Square Notch)

The specimen started to tear at the edges when it failed. In this specimen the yield was greatest at the edges. This can be shown in the photographs by the way the vertical lines bow out and the increase in the size of the squares. There is also considerable yield in the center of the bar. The yield was over a 1½" length.

3A and 3B (Hack Saw Cut)

This specimen started to tear at the edges. The fact that it did start to tear at the edges was more pronounced in this specimen than in any other. There was a high concentration of stress around the bottom of the hack saw cut. The yield was over a 1¼" length.

4A and 4B (The V Notch)

This specimen started to tear at the edges. The stress concentration was at the bottom of the V notch. The yield was over a 2 3/8" length.

5A and 5B

This piece broke in the center first as did the control. The bar had its main stress concentration in the center as did the control. However it also had stress concentration at the change in section as did the other notched specimen. This can be proved by observing that the lines bow outward near the middle and inward at the change in section. The yield was distributed over 1 3/4".

CONCLUSIONS

Ultimate Strength Results

The reason that the bars had their corresponding ultimate strengths can be shown by comparing the notches. The bar with the severest notch, the V notch, tested highest in ultimate strength. The hack saw cut was the second severest and was correspondingly second in ultimate strength. The square notch tested third highest, the hollowed out notch was fourth and the control bars were lowest in ultimate strength.

The more severe the notch the more it resists the necking down action. This can be proved by observing the pictures after failure. The necking down action in the severely notched bars was mainly confined to the long side of the cross-sectional area. The control bar necked down on both sides of the cross sectional area. If there is little necking down then there is more area to resist the load and this accounts for the range of ultimate strength.

The Proportional Limit

The proportional limit is defined as the greatest stress which a material is capable of developing without deviating from the law of proportionality of stress to strain.

This is a common definition of the proportional limit but it does not mention anything about the geometric shape of the body. In the tests all the bars were of the same material and the geometric shape of the bar was changed. The proportional limit of the bars varies considerably with a change in geometric shape.

The V notch was highest in proportional limit, the control was second, the square and the hollowed out notch were about the same and the hack saw cut was the lowest. This tends to prove the idea that stress is transmitted in lines in ductile materials. The V notch offers the least resistance to flow of the stress lines and therefore has the highest proportional limit. The stress lines flow down the sides of the V and the metal on the sides actually help raise the proportional limit because the reduction of area is over such a small length. The control tested second highest in proportional limit because there was no stress concentration. The square notch and round notch had the bad effect of stress concentration. The metal at the sides of the notches did not help in the proportional limit because of the reduced area was over a longer length than in the case of the V notch.

The hack saw had the highest stress concentration and therefore the lowest proportional limit.

This can also be shown by the way the curves slope after the proportional limit.

Yield Point and Yield Strength

The yield point and yield strength are about the most important data obtained from the test because they are used for determining the working stress for structual members.

In the case of structual steel the yield strength is defined at .2 per cent permanent set limit. It can be observed from the graphs that the bars were in the following order of yield strength, V notch, hack saw cut, square notch and control about the same, and the hollowed out bar was the lowest.

General Conclusions

These static tensil tests tend to prove that ductile steel bars with a severe notch are stronger than a bar with a less severe notch or a bar with the notch effect removed. This is due to the fact that as the severity of the notch increases, deformation decreases. In a ductile material the metal around the notch helps the strength of the bar if the notch is severe enough. I recommend that more tests be run to confirm the above results. The shape and variety of notches could also be increased to give more data on which to base conclusions.

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