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THE PERFORMANCE OF BOLTED TIMBER JOINTS WITH DEPARTURES FROM NEW ZEALAND CODE REQUIREMENTS

J.T. Gerlich

PREFACE

The work described in this report is part of a research programme being carried out by BRANZ to prepare design information on bolted timber connections, loaded in shear, in applications which are not adequately covered by currently available codes of practice and timber design handbooks.

ACKNOWLEDGEMENT

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This report is intended for research workers and designers in the field of timber engineering.

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J.T. Gerlich

REFERENCE

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From Construction Industry Thesaurus, BRANZ edition: Bolts; Codes of practice; Deflection; Joints; Loads; New Zealand; Shear; Standards; Stiffness; Structural design; Test procedures; Timber.

ABSTRACT

This report describes a series of tests carried out on bolted timber joints loaded in single shear and with departures in end and edge distances, bolt hole size and washer size from the requirements of New Zealand Standard NZS 3603: 1981 Code of Practice for Timber Design. The aim was to quantify the effect of such departures on joint performance.

Joints with 12mm diameter galvanised mild steel bolts and constructed using *Pinus radiata* were tested in tension both parallel and perpendicular to the grain and at both the green and dry stage of conditioning.

Results and conclusions are detailed in the report and are summarised as:

- An increase in bolthole diameter did not affect joint performance.
- A (weak) correlation between joint strength and timber density was only found with joints assembled dry and tested dry.
- Timber thickness had only a significant effect on strength for joints assembled dry and tested dry perpendicular to the grain.
- Code design loads appear conservative. With the exception of joints tested perpendicular to the grain and having reduced end distances, the design loads calculated from the test results are all in excess of code loads.
- Of all joints tested perpendicular to the grain 20 per cent failed due to splitting of the member away from the joint. This would indicate a possible strength upper limit regardless of bolt size.
- Reducing edge and/ or end distances significantly reduced joint strength. Intermediate end distances were tested for joints loaded parallel to the grain and these gave intermediate results.
- The effect of coach bolts or small washers on ultimate loads and the load/ deflection characteristic was found to be significant.

CONTENTS

	page
INTRODUCTION	1
Previous Work	1
Future Work	2
EXPERIMENTAL DESIGN	2
Timber	2
Number of Replicates	2
Selection of Joint Variables and Combinations	3
Stage 2 Test Programme	3
CONSTRUCTION AND CONDITIONING OF SPECIMENS	6
Timber Grade and Sorting	6
Bolt Holes	6
Assembly	6
Conditioning	7
TEST METHOD	7
Arrangement	7
Loading Rate	7
Test Procedure	8
ANALYSIS OF DATA	8
Data Points	8
Principles of Analysis	9
RESULTS	9
Presentation of Data in Appendices	9
Displacements	10
Timber Density	10
Moisture Content	10
Bolt Hole Size	11
Effect of Variables and Combinations	11
Basic Working Loads to NZS 3603	12
DISCUSSION	15
Code Values	15
Timber Thickness	15
Density	15
Failure Mode Perpendicular to the Grain	15
End Distance Perpendicular to the Grain	16
Bolt Hole Size	16
CONCLUSIONS	16
REFERENCES	18

TABLES		page
Table 1:	Construction schedule for joints loaded parallel to the grain	4
Table 2:	Construction schedule for joints loaded perpendicular to the grain	5
Table 3:	Effects of variables and combinations for joints loaded parallel to the grain	11
Table 4:	Effects of variables and combinations for joints loaded perpendicular to the grain	12
Table 5:	Basic working loads for joints loaded parallel to the grain	13
Table 6:	Basic working loads for joints loaded perpendicular to the grain	14

FIGURES	page
Figure 1: General test arrangements	19
Figure 2: Perpendicular to the grain short end distance specimen	20
Figure 3: Perpendicular to the grain mid-beam specimen	21
Figure 4: Parallel to the grain specimen	22
Figure 5: Idealised load/displacement graph	23
Figure 6: Density effect for group c	24
Figure 7: Density effect for group f	24

APPENDIXES	Page
APPENDIX 1: SELECTION OF JOINT VARIABLES AND COMBINATIONS	25
APPENDIX 2: DENSITY CONVERSIONS	32
APPENDIX 3: RAW DATA	34
APPENDIX 4: FAILURE MODES	38
APPENDIX 5: SIGNIFICANT EFFECTS	41
APPENDIX 6: LOAD DISPLACEMENT GRAPHS	45
APPENDIX 7: KEY TO JOINT CODES	78

INTRODUCTION

The experimental work described in this report forms the second stage of a research programme to prepare design information for bolted timber joints which are loaded in shear and have deviations from the requirements of New Zealand Standard NZS 3603: 1981 Code of practice for Timber Design.

The variables studied are:

- Connections which have edge and end distances less than the specified minimum.
- Connections which have smaller washers than those specified.
- Connections which have larger holes than those specified.

Design information contained in NZS 3603 specifies limiting conditions under which maximum design bolt loads can be used. If these conditions are not fulfilled, which is often difficult in practice, failure to comply implies an allowable joint load of zero.

Consideration is given to the load/deflection data for these bolted joints, their ultimate strength and failure modes. This information is often needed by designers but is not readily available in codes of practice or timber design handbooks which usually specify working loads only.

Previous work

A survey of past literature (Harding, 1982) confirmed that insufficient detailed and replicated information exists on bolted timber joints loaded in shear. Some data indicates that, as a result, present code design rules may be unduly restrictive.

An informal survey showed that, within the New Zealand building industry, a lack of confidence exists in present design requirements which are considered to be based on component tests with limited relevance to the behaviour of a structure as a whole. No allowances are made for conditions occurring in practice and, probably as a result, code provisions are commonly violated.

A first series of tests (Stage 1) was carried out to establish the effect of a selected number of variables on the performance of bolted timber joints loaded in single shear. It was found that the performance for all joints was significantly reduced with reductions in end distances. Reductions in edge distance significantly affected perpendicular to the grain joints. Increasing bolt hole size did not significantly affect joint performance. Other effects are detailed in the report on this experimental work (Fowkes and Harding, 1986).

The tests reported on in the following pages were carried out to more fully investigate the effects established previously, and to determine reliable performance values for bolted joints with the variables and combinations studied.

Future Work

Based on the results of the experimental work described in this report, recommendations for design office use will be produced covering 12mm diameter bolts in *Pinus radiata*, loaded in single shear.

EXPERIMENTAL DESIGN

The test programme was designed to yield design data for joints which depart from the Code in details of end and edge distances, bolt hole diameter and washer size. Code joints were included as controls and to verify current Code values.

Consistent with the previous experimental work, all testing was carried out in tension on two member, single-bolt joints.

Joints were tested both perpendicular and parallel to the grain and at moisture contents of above 30 per cent (wet) and below 18 per cent (dry). Six subgroups were constructed:

Perpendicular to the grain

assembled wet, tested wet
assembled wet, tested dry
assembled dry, tested dry

Parallel to the grain

assembled wet, tested wet (wet-wet)
assembled wet, tested dry (wet-dry)
assembled dry, tested dry (dry-dry)

Timber

Only one timber species, *Pinus radiata*, was included in this investigation. This is by far the most commonly used timber for construction in New Zealand.

Timber density had limited effect on joint performance in the previous test series, affecting the design loads for parallel dry joints only. The linear strength versus density relationship as suggested by the reference density modification in NZS 3603 was not confirmed. To avoid unnecessarily large variations in density and to have an average New Zealand density throughout the test programme, all timber was obtained from the Rotorua district in the central part of the North Island. All timber was green gauged, No.1 framing grade, and copper chrome arsenate (CCA) treated to the Timber Preservation Authority (TPA) classification H3.

Number of replicates

Australian Standard AS 1649: 1974 Determination of Basic Working Loads for Metal Fasteners for Timber, specifies a minimum of ten replicates when only one level of a variable is being investigated and a minimum of six replicates where tests are conducted at more than one level of a single variable.

For any one type of joint a number of eight replicates was decided on. This was somewhat subjective, but was based on the means and variances found in the previous experimental work. For a coefficient of variation of around 20 per cent, which can be expected for ultimate loads, the 95 per cent confidence limits are within 14 per cent of the joint mean when using a number of eight replicates.

Selection of Joint Variables and Combinations

The background and justification for the selection of the variables and combinations of variables incorporated in the test programme is given in Appendix 1.

Stage 2 Test Programme

The following tables give the construction schedule for all specimens tested.

Variation Code 0 indicates a control joint, constructed in accordance with Code requirements. Variations are coded: B bolt hole size, A timber thickness, C washer size, C1 coach bolt, D edge distance, E end distance and E1 intermediate end distance. A cross (x) is entered to indicate the variation for any particular joint code.

TABLE 1: Construction schedule for joints loaded parallel to the grain

a. PARALLEL TO THE GRAIN WET WET (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.	END DIST.		
	mm 100	mm 50	mm 13	mm 15	mm 50 (sq)	mm 32 (dia)			mm 0	mm 2D	mm 7D
O	x		x		x			x	x		
B	x			x	x			x	x		
BA		x		x	x			x	x		
BC	x			x		x		x	x		
BC1	x			x			x	x	x		
BE	x			x	x			x		x	
BE1	x			x	x			x			x
BAC		x		x		x		x	x		
BAE		x		x	x			x		x	
BCE	x			x		x		x		x	
BACE		x		x		x		x		x	
BAC1		x		x			x	x	x		

b. PARALLEL TO THE GRAIN WET DRY (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.	END DIST.		
	mm 100	mm 50	mm 13	mm 15	mm 50 (sq)	mm 32 (dia)			mm 0	mm 2D	mm 7D
O (A)		x	x		x			x	x		
B (A)		x		x	x			x	x		
BC (A)		x		x		x		x	x		
BC1 (A)		x		x			x	x	x		
BE (A)		x		x	x			x		x	
BE1 (A)		x		x	x			x			x
BCE (A)		x		x		x		x		x	
BCE1(A)		x		x		x		x			x

c. PARALLEL TO THE GRAIN DRY DRY (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.	END DIST.		
	mm 100	mm 50	mm 13	mm 15	mm 50 (sq)	mm 32 (dia)			mm 0	mm 2D	mm 7D
O (A)		x	x		x			x	x		
B (A)		x		x	x			x	x		
BC (A)		x		x		x		x	x		
BC1 (A)		x		x			x	x	x		
BE (A)		x		x	x			x		x	
BE1 (A)		x		x	x			x			x
BCE (A)		x		x		x		x		x	
BCE1(A)		x		x		x		x			x

Table 2: Construction schedule for joints loaded perpendicular to the grain

d. PERPENDICULAR TO THE GRAIN WET WET (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.		END DIST.	
	mm	mm	mm	mm	mm	mm		mm	mm	mm	mm
	100	50	13	15	50	32	0	4D	2.5D	300	4D
					(sq)	(dia)					
O	x		x		x			x		x	
B	x			x	x			x		x	
BA		x		x	x			x		x	
BC	x			x		x		x		x	
BC1	x			x			x	x		x	
BD	x			x	x				x	x	
BE	x			x	x			x			x
BAD		x		x	x				x	x	
BCE	x			x		x		x			x
BDE	x			x	x				x		x
BC1E	x			x			x	x			x
BAC1		x		x			x	x		x	

e. PERPENDICULAR TO THE GRAIN WET DRY (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.		END DIST.	
	mm	mm	mm	mm	mm	mm		mm	mm	mm	mm
	100	50	13	15	50	32	0	4D	2.5D	300	4D
					(sq)	(dia)					
O	x		x		x			x		x	
B	x			x	x			x		x	
BA		x		x	x			x		x	
BC	x			x		x		x		x	
BC1	x			x			x	x		x	
BD	x			x	x				x	x	
BE	x			x	x			x			x
BAC		x		x		x		x		x	
BCE	x			x		x		x			x
BDE	x			x	x				x		x
BC1E	x			x			x	x			x
BAC1		x		x			x	x		x	

f. PERPENDICULAR TO THE GRAIN DRY DRY (Eight specimens each)

VARIATION CODE	TIMBER THICKNESS		BOLTHOLE SIZE		WASHER SIZE		COACH BOLT	EDGE DIST.		END DIST.	
	mm	mm	mm	mm	mm	mm		mm	mm	mm	mm
	100	50	13	15	50	32	0	4D	2.5D	300	4D
					(sq)	(dia)					
O	x		x		x			x		x	
B	x			x	x			x		x	
BA		x		x	x			x		x	
BC	x			x		x		x		x	
BC1	x			x			x	x		x	
BD	x			x	x				x	x	
BE	x			x	x			x			x
BAC		x		x		x		x		x	
BCE	x			x		x		x			x
BDE	x			x	x				x		x
BC1E	x			x			x	x			x
BAC1		x		x			x	x		x	

CONSTRUCTION AND CONDITIONING OF SPECIMENS

Timber Grade and Sorting

Surplus timber from Stage 1 testing was carefully checked for decay after prolonged storage and used to begin testing in the main group 'perpendicular to the grain'. In the subgroups 'wet-dry' and 'dry-dry', three out of each eight joints were constructed using surplus Stage 1 timber. To bring this timber back to its 'green' state for the 'wet-dry' subgroup, lengths sawn to the joint member size were submerged in a purpose-made basin under weight control until a moisture content of 80 per cent was reached. The timber was subsequently left to dry until close to 40 per cent moisture content at which stage joints were drilled and assembled.

The bulk of the Stage 2 timber was ordered in two lots. The remainder of the timber for joints to be tested perpendicular to the grain was ordered and processed first. Near the end of all testing in this group an order was placed for the timber to be used for joints to be tested parallel to the grain. The orders were separated to avoid early drying or decay as a result of prolonged storage.

Timber was generally cut to provide clear test specimens. Although small knots and other minor imperfections were present, they were in no case of a size or so positioned as to affect joint performance. However, for the deep members required for the testing perpendicular to the grain, some pith was present in some specimens at roughly half the depth of the member.

When cutting up the timber, each length was first given a number (1,2,3 etc.) and marked to be sawn into test pieces. In addition, three moisture and density samples were taken from each timber length. One of these samples was taken out of the middle third of a length and the others close to each end. A minimum of 100mm, or more depending on the end splitting which had occurred, was cut off the ends of each length and rejected. Test pieces were marked and given the timber length number before the timber was cut. All test pieces to be used within a subgroup were laid out, timber length number down, and were marked at random with the final test variation code and specimen number. The timber length numbers, marked on the reverse side, were added later to achieve a randomised distribution of timber properties within the subgroup.

Bolt Holes

Hole locations were accurately marked and the test pieces held in position using a purpose made jig. Holes were drilled perpendicular to the face of the timber using a drill press and twist drill bits. A medium drill speed and rate of penetration was used to ensure a consistent quality of cut.

Assembly

Joints tested in the main group parallel to the grain were, as much as practicable, assembled with test pieces and companion pieces cut from the adjacent sections of a timber length.

No similar matching was undertaken for specimens loaded perpendicular to the grain. Each test piece was paired with a companion piece which was loaded in tension parallel to the grain. This is the most usual arrangement in practice. A 'safe' end distance of 100mm was used for the companion piece to ensure that the test piece was the weakest link.

All 'wet-wet' and 'dry -dry' joints were firmly tightened with a 200mm spanner to approximately finger-tight plus a full turn, prior to testing.

All 'wet-dry' joints were assembled ~~in the test rig~~ and firmly tightened, as described above, and left to dry. Shrinkage of the joints caused loosening of the connection in all cases. Nuts were retightened finger-tight prior to testing.

Conditioning

All joints intended for testing whilst 'wet' did not require conditioning and were tested as soon as possible after assembly. In the case of any delay, joints were wrapped tightly in polythene until the time of testing to inhibit drying.

Joints in the subgroups 'wet-dry' were assembled 'wet' and stored under well-ventilated conditions indoors. Regular checks were made on moisture content using a resistance moisture meter, until an equilibrium moisture content of below 18 per cent was obtained.

Green timber lengths, intended for joints in the subgroup 'dry-dry', were similarly stored and regularly checked until a moisture content of below 18 per cent was obtained, at which stage the timber was processed into test joints.

TEST METHOD

Arrangement

Tests were carried out in tension using the arrangement previously used in the Stage 1 testing programme as illustrated in Figure 1.

For the testing of joints loaded parallel to the grain straps were used between the timber members and the universal joints of the test equipment (Figure 1a).

A similar arrangement was used for the testing of 'beam-end' joints loaded perpendicular to the grain (Figure 1c). For the simulated 'mid-beam' joints a 400mm span steel yoke was used (Figure 1b).

Loading Rate

Flexibility provided by the test arrangement results in considerable variations in the rate of relative movement in the test joint for a constant machine crosshead speed. In the early linear portion of the joint load/slip curve the machine crosshead speed is approximately twice the joint test speed because of slippage of the specimen connections to the testing machine. Beyond yield point the joint test speed accelerates smoothly to be close to crosshead speed near ultimate load.

To reduce testing time, and to more closely represent loading conditions in service, a machine crosshead speed of 12mm per minute was selected for all joints, resulting in approximately a 6mm per minute displacement rate at the joint over the linear portion of the load/displacement curve.

Although higher than past practice for bolted joints, similar speeds have been used for nailed timber joints. Previous research (Harding, 1982) indicates that variations in speed up to 12mm per minute have little or no effect on load/displacement curves or ultimate loads. The present availability of electronic transducers and data-logging equipment permits satisfactory use of somewhat higher speeds.

Test Procedure

Specimens were placed in the test apparatus as shown in Figures 2, 3 and 4. They were loaded in shear by applying a tensile force along the central axis of the joint either perpendicular or parallel to the grain, as appropriate.

Loads were applied using a 100kN servo-jack unit mounted in a Dartec M1000/RE straining frame. A 100kN capacity, resistance strain gauge load cell was used for measuring loads to an accuracy within 1 per cent of reading down to 2kN. A transducer incorporated in the system measured crosshead displacement. Joint movement was measured by two spring-return Sakae Model 20FLP100A linear motion potentiometers, with an accuracy of 0.25 per cent of reading. One potentiometer was placed on either side of the bolt. Deflection was taken as the mean of the two readings.

Simultaneous readings of load, deflection and cross head movement were recorded using a Hewlett-Packard (HP) 3497A data acquisition unit and a HP87 personal computer. Data was read at intervals of 1 second during each test and stored on floppy disks. In addition, and as a back-up, an independent load and crosshead displacement recording was obtained using a x-y plotter connected to the test apparatus.

The failure mode of each joint was noted and, immediately after testing, sections were cut from each specimen to determine wood density and moisture content.

Densities were determined in accordance with the provisions of NZS 3603:1981 Appendix A and moisture contents by the method given in Appendix C of NZSS 632:1967 Standard specification for the kiln drying of timber. Densities are quoted as 'oven-dry density' and were calculated using the formula: oven-dry weight/ oven-dry volume. A conversion table from 'oven-dry density' to 'basic density' is attached in Appendix 2 and was calculated in accordance with Collins (1983).

ANALYSIS OF DATA

Data Points

The algorithm illustrated in Figure 5 defines the characteristic stages of the load/deflection curve for a bolted joint loaded in shear.

Proportional limit load and displacement are defined as those occurring when the slope of the load/deflection drops to 70 per cent of its maximum after having passed it.

Yield point is defined as the intersection of the load/deflection curve with a straight line which is offset 0.05D from, and runs parallel with the line of initial slope which connects the two points with a slope equal to 70 per cent of the maximum. For joints in the subgroups 'wet-wet' and 'dry-dry' which were tested in the tight condition, no significant take-up distance was noted and the line of initial slope was taken as the line connecting the point of proportional limit with the origin.

Ultimate load and displacement are presented and, in addition, loads occurring at 0.5D and 1.0D displacements are included to provide intermediate data.

Principles of Analysis

The data were analysed separately in each of the six groups using an analysis of covariance in which the 'treatments' were the joint variations and the covariables were moisture content and density.

The distribution of loads and displacements were slightly skewed indicating some departure from normality. The standard deviation of ultimate loads also appeared to increase proportionally with mean ultimate load, indicating that a logarithmic transformation of ultimate loads would be required to improve symmetry and, in most cases, stabilise variance. For consistency, the analysis of covariance for all loads and displacements was based on logged data (natural logarithm) assuming a log-normal distribution.

Comparisons between joint means were used to test for the statistical significance of main effects and interactions of factors representing a single departure from the Code.

RESULTS

Presentation of Data in Appendices

Appendix 3 lists the raw data in tabulated form for each group of eight identical specimens. The mean is presented as well as the standard deviation for the eight observations.

Appendix 4 describes the failure mode of each specimen.

Appendix 5 tabulates the significant effects of variables and combination of variables on joint performance. Statistical significance is indicated at the 95% and 99% confidence levels. Deviations from the control means at the characteristic points along the load/deflection curve are estimated whenever a significant effect is identified.

Appendix 6 graphically presents the data for each group of eight identical specimens up to the 1.0D displacement point. Curves were drawn to best fit the means of the data points. Ultimate load and displacement for each specimen is tabulated separately.

Displacements

There was a large spread in the displacement data and only the general trends are summarised as follows.

For joints in the 'loose' condition in the subgroups 'wet-dry' a take-up distance could clearly be identified in most cases.

Where the ultimate displacement was affected by reduced edge and/or end distances, the reductions were generally in line with expectations based on the reduction in loads.

A reduction in washer size, or the use of a coach bolt generally had an effect on the early stiffness of the joint. When comparing the slope of the load/ displacement graph up to the yield point, the calculated stiffness (YLL/YLD) using a round washer or coach bolt was in the order of 60 per cent of the slope calculated for joints with 50mm square washers. Further along the load/ displacement curve, differences became less pronounced.

Timber Density

Timber density was only found to have a significant effect on all loads in group c and on ultimate loads and ultimate displacements in group f. The density effect in these 'dry-dry' groups is illustrated in Figures 6 and 7. Plotted are the ultimate loads of all specimens in the group, adjusted to the group mean, against specimen density. Adjustment for each joint was done by subtracting or adding the difference between the particular joint variation mean and the overall mean.

Based on the logged data, the slope estimates are approximately the relative increase in ultimate load for a unit increase in density. These estimates are based on and appear linear over the relatively narrow range of densities tested. The figures for the results based on raw data have been included for comparison.

Group	Slope (logs)	Slope (raw)
c	0.0017	0.033
f	0.0012	0.013

These estimates were used in the analysis to adjust the logged mean results for eight identical specimens to the group mean density. The effect of density is thereby removed, so that any difference between the adjusted means must be attributable to the type of joint.

Moisture Content

Within the 'wet' range (groups a and d) statistical significance of the effect of moisture content was indicated, but associations between joint configuration and moisture content were found. For example, in group a, thin joints were moister and denser. Therefore the data could not be used to estimate the effect of moisture content in the 'wet' range. In the earlier study (Fowkes and Harding, 1986) no significant effect was found.

Comparison of ultimate loads for similar joints between the 'wet' and 'dry' groups gave an average strength reduction factor of 0.82 for joints

tested wet compared to those tested dry. Reduction factors ranged from 0.68 to 1.13.

Bolt Hole Size

The variation in bolt hole size was tested throughout the entire experimental programme and was not found to have a significant effect on joint performance when compared with the code joint. The results of tests on joints with this variation only were combined with the code joint results to form the control means.

Effect of Variables and Combinations

The following tables give a summary of the effects of variables on ultimate (and hence design) loads. The statistical analysis was based on logged data and comparison of geometric means. Significance is indicated at the 95% confidence level. Effects were calculated as the ratio of all joints containing the variable, to those joints without the variable. The mean ultimate load or design value for joints containing a variable or combination of variables is expressed as a percentage of the control value.

Table 3: Effects of variables and combinations for joints loaded parallel to the grain

Group a. Parallel to the grain, assembled wet tested wet

Control&B	100	A	C	C1
A	100	-----	-----	-----
C	87+	87	-----	-----
C1	88+	68#	-----	-----
E	76	76	53#	*
E1	76	*	*	*

Group b. Parallel to the grain, assembled wet tested dry

Control&A&B	100	C	C1
C	75	----	-----
C1	71	----	-----
E	53	40	*
E1	78	58	*

Group c. Parallel to the grain, assembled dry tested dry

Control&A&B	100	C	C1
C	75	----	-----
C1	69	----	-----
E	64	50	*
E1	87+	65	*

Table 4: Effects of variables and combinations for joints loaded perpendicular to the grain

Group d. Perpendicular to the grain, assembled wet tested wet

Control&B	100	A	C	C1	D
A	100	-----	-----	-----	-----
C	83	*	-----	-----	-----
C1	80	80	-----	-----	-----
D	81	81	*	*	-----
E	54	*	45	43	44

Group e. Perpendicular to the grain, assembled wet tested dry

Control&B	100	A	C	C1	D
A	100	-----	-----	-----	-----
C	90+	90	-----	-----	-----
C1	92+	92	-----	-----	-----
D	59	*	*	*	-----
E	55	*	50	50	47#

Group f. Perpendicular to the grain, assembled dry tested dry

Control&B	100	A	C	C1	D
A	69	-----	-----	-----	-----
C	77	53	-----	-----	-----
C1	84	58	-----	-----	-----
D	70	*	*	*	-----
E	61	*	47	51	43

Indicates an interaction between variables was found. In all other cases the combined effects are equal to the product of the individual effects of variables.

+ Indicates an estimate is entered although no statistical significance was identified in the particular group at the 95% confidence level as a result of this test programme. An effect can reasonably be expected based on identified significance in other groups.

* Indicates the combination was not tested.

Basic Working Loads to NZS 3603

'Basic working loads' were derived in accordance with the recommendations outlined in NZS 3603 and the requirements of AS 1649 and are listed in Tables 5 and 6. A density modification consistent with the correlation found in the analysis was applied for the 'dry-dry' subgroups only. The figures in brackets are those adjusted to the NZS 3603 reference density using the density correlation established from this test programme. To determine the 5 per cent lower probability limits a pooled standard deviation was used derived from all results within a subgroup and assuming a lognormal distribution.

Table 5: Basic working loads for joints loaded parallel to the grain

Group a. Parallel to the grain, assembled wet tested wetCode value: $0.7 \times 3.09 \text{ kN} = 2.16 \text{ kN}$

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
a0	5.77	5.89	5.77 kN
aB	5.21	5.40	5.21 kN
aBA	5.68	5.83	5.68 kN
aBC	4.78	4.91	4.78 kN
aBC1	4.94	4.95	4.94 kN
aBE	4.17	4.26	4.17 kN
aBE1	4.17	4.32	4.17 kN
aBAC	5.11	5.32	5.11 kN
aBAE	3.56	3.71	3.56 kN
aBCE	2.83	2.90	2.83 kN
aBACE	2.63	2.71	2.63 kN
aBAC1	3.71	3.85	3.71 kN

Group b. Parallel to the grain, assembled wet tested dry

Code value: 3.09 kN

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
bA	7.51	7.57	7.51 kN
bAB	7.63	7.64	7.63 kN
bABC	5.70	5.68	5.68 kN
bABC1	5.40	5.41	5.40 kN
bABE	4.02	4.06	4.02 kN
bABE1	5.86	5.91	5.86 kN
bABCE	3.73	3.78	3.73 kN
bABCE1	4.74	4.81	4.74 kN

Group c. Parallel to the grain, assembled dry tested dry

Code value: 3.09 kN

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
cA	6.78 (6.35)	7.27 (6.63)	6.35 kN
cAB	7.05 (6.70)	7.59 (7.05)	6.70 kN
cABC	5.27 (4.85)	5.59 (5.12)	4.85 kN
cABC1	4.79 (4.46)	5.08 (4.74)	4.46 kN
cABE	4.51 (4.09)	4.82 (4.41)	4.09 kN
cABE1	6.17 (5.71)	6.55 (5.94)	5.71 kN
cABCE	3.78 (3.18)	4.02 (3.55)	3.18 kN
cABCE1	4.44 (3.74)	4.72 (4.07)	3.74 kN

Table 6: Basic working loads for joints loaded perpendicular to the grain

Group d. Perpendicular to the grain, assembled wet tested wetCode value: $0.7 \times 2.07 \text{ kN} = 1.45 \text{ kN}$

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
dO	3.00	3.17	3.00 kN
dB	3.13	3.36	3.13 kN
dBA	2.87	3.07	2.87 kN
dBC	2.52	2.70	2.52 kN
dBC1	2.45	2.63	2.45 kN
dBD	2.46	2.64	2.46 kN
dBE	1.67	1.77	1.67 kN
dBAD	2.27	2.42	2.27 kN
dBCE	1.31	1.40	1.31 kN
dBDE	1.47	1.55	1.47 kN
dBC1E	1.36	1.43	1.36 kN
dBAC1	2.18	2.32	2.18 kN

Group e. Perpendicular to the grain, assembled wet tested dry

Code value: 2.07 kN

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
eO	3.90	3.91	3.90 kN
eB	3.71	3.78	3.71 kN
eBA	3.31	3.39	3.31 kN
eBC	3.37	3.46	3.37 kN
eBC1	3.45	3.52	3.45 kN
eBD	2.17	2.26	2.17 kN
eBE	2.04	2.12	2.04 kN
eBAC	2.92	3.01	2.92 kN
eBCE	1.91	1.98	1.91 kN
eBDE	1.74	1.81	1.74 kN
eBC1E	1.88	1.92	1.88 kN
eBAC1	2.92	3.00	2.92 kN

Group f. Perpendicular to the grain, assembled dry tested dry

Code value: 2.07 kN

	MEAN ULT/ 4	5% LPL/ 2.8	BWL
fO	3.82 (3.75)	3.90 (3.82)	3.75 kN
fB	4.12 (4.04)	4.22 (4.14)	4.04 kN
fBA	2.79 (2.68)	2.84 (2.72)	2.68 kN
fBC	3.06 (2.96)	3.15 (3.04)	2.96 kN
fBC1	3.20 (3.21)	3.28 (3.29)	3.21 kN
fBD	2.86 (2.67)	2.96 (2.75)	2.67 kN
fBE	2.58 (2.37)	2.59 (2.36)	2.36 kN
fBAC	2.46 (2.40)	2.53 (2.47)	2.40 kN
fBCE	2.07 (1.91)	2.14 (1.97)	1.91 kN
fBDE	1.87 (1.76)	1.92 (1.80)	1.76 kN
fBC1E	2.18 (1.98)	2.21 (1.99)	1.98 kN
fBAC1	2.32 (2.30)	2.40 (2.37)	2.30 kN

DISCUSSION

Code Values

Apart from short end joints loaded perpendicular to the grain all joints exceeded the code value for basic working load despite some severe reductions in joint specification.

The control joints tested parallel to the grain all achieved basic working loads of more than twice the code value.

The basic working loads for control joints tested perpendicular to the grain were close to twice the code value.

Timber Thickness

Timber thickness was only found to have a significant effect on ultimate loads for joints tested dry and perpendicular to the grain.

Generally, this timber thickness correlation appears in agreement with NZS 3603. In the Code no increase is allowed in basic working loads for an increase in effective thickness beyond 50mm when joints are loaded parallel to the grain. For joints loaded perpendicular to the grain the load increase stops at just over 100mm effective timber thickness. The thin joints tested in this programme had an actual effective thickness of 94mm, which would indicate a slight reduction in ultimate load.

Density

When working out basic working loads (BWL) in accordance with NZS 3603 Appendix A, the results from calculations to AS 1649 have to be modified for density using the formula:

$$BWL = BWL \text{ at test } \times \text{Reference density} / \text{Average test density}$$

This formula suggests a fairly strong correlation between joint strength and timber density.

This test programme only indicates a statistically significant effect of timber density for joints in 'dry-dry' subgroups. The slopes of 0.033 kN (group c) and 0.013 kN (group f) for each unit change in density are approximately one third and one seventh respectively of the correlation suggested by NZS 3603.

This lack of density correlation was also found by Jacks and Thurston (1985).

Failure Mode Perpendicular to the Grain

Out of all joints tested perpendicular to the grain, 20 per cent failed in tension by splitting below the level of a horizontal line through the joint. Although for the 12mm diameter bolts tested these failures occurred at similar load levels to the failures through the joint, or in some cases even simultaneously, the failure mode suggests independence from bolt diameter. Increasing bolt diameter may not necessarily increase design

loads correspondingly as suggested by current Code provisions. Similar failure modes have been reported in practice. Further research into failures perpendicular to the grain, when load is applied in tension, is desirable.

End Distance Perpendicular to the Grain

NZS 3603 does not specify a minimum end distance with joints loaded perpendicular to the grain. Reducing the end distance to 4D had a marked effect on joint performance. Of all joints tested only the perpendicular-short-end variation resulted in basic working loads below current Code values. More research into the effect of end distance for joints loaded perpendicular to the grain is desirable. Until then an end distance somewhat greater than 4D is recommended to achieve Code design loads.

Bolt Hole Size

No adverse effect of increased bolt hole size was established. This confirms the Stage 1 finding. It would be desirable to relax the current NZS 3603 requirement of $D + 1.5\text{mm}$ somewhat to facilitate easier site installation through greater tolerances. Problems associated with the driving of bolts through tight holes and timber shrinkage could also be reduced by increasing the allowable bolt hole size.

CONCLUSIONS

For two member joints constructed out of *Pinus radiata* with a single 12mm diameter bolt, the basic working loads derived from this test programme are in excess of current Code values, with the exception of joints tested perpendicular to the grain and having a reduced end distance.

Further investigation into the effect of bolt diameter is recommended, particularly where it applies to joints loaded perpendicular to the grain since a large percentage of failure modes in this test programme suggest independence from bolt diameter.

The effect of timber thickness on joint performance was found to be generally in line with current Code provisions.

It appears that the density modification currently suggested in Appendix A of NZS 3603 is inappropriate.

Increasing the maximum bolt hole size from the current NZS 3603 requirement of $D + 1.5\text{mm}$ to the $D + 3.0\text{mm}$ used in this test programme did not appear to have a significant effect on joint performance.

Decreased washer size or the use of a coach bolt resulted in a decrease in joint strength to about 80 per cent on average throughout the test programme.

Considerable reductions in joint strength occurred with decreased end distances for joints loaded parallel to the grain. The intermediate end distance tested gave intermediate results suggesting a linear relationship.

Marked reductions in joint strength were noted when reducing the edge and/or end distance for joints loaded perpendicular to the grain. Current Code design loads were not achieved with the tested end distance of $4D$, although reliable and useful design loads can be derived with this variation. Further study is recommended into the effect of end distance on the performance of joints loaded perpendicular to the grain.

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Standards Association of Australia. 1974. Determination of basic working loads for metal fasteners for timber. AS 1649. Sydney.

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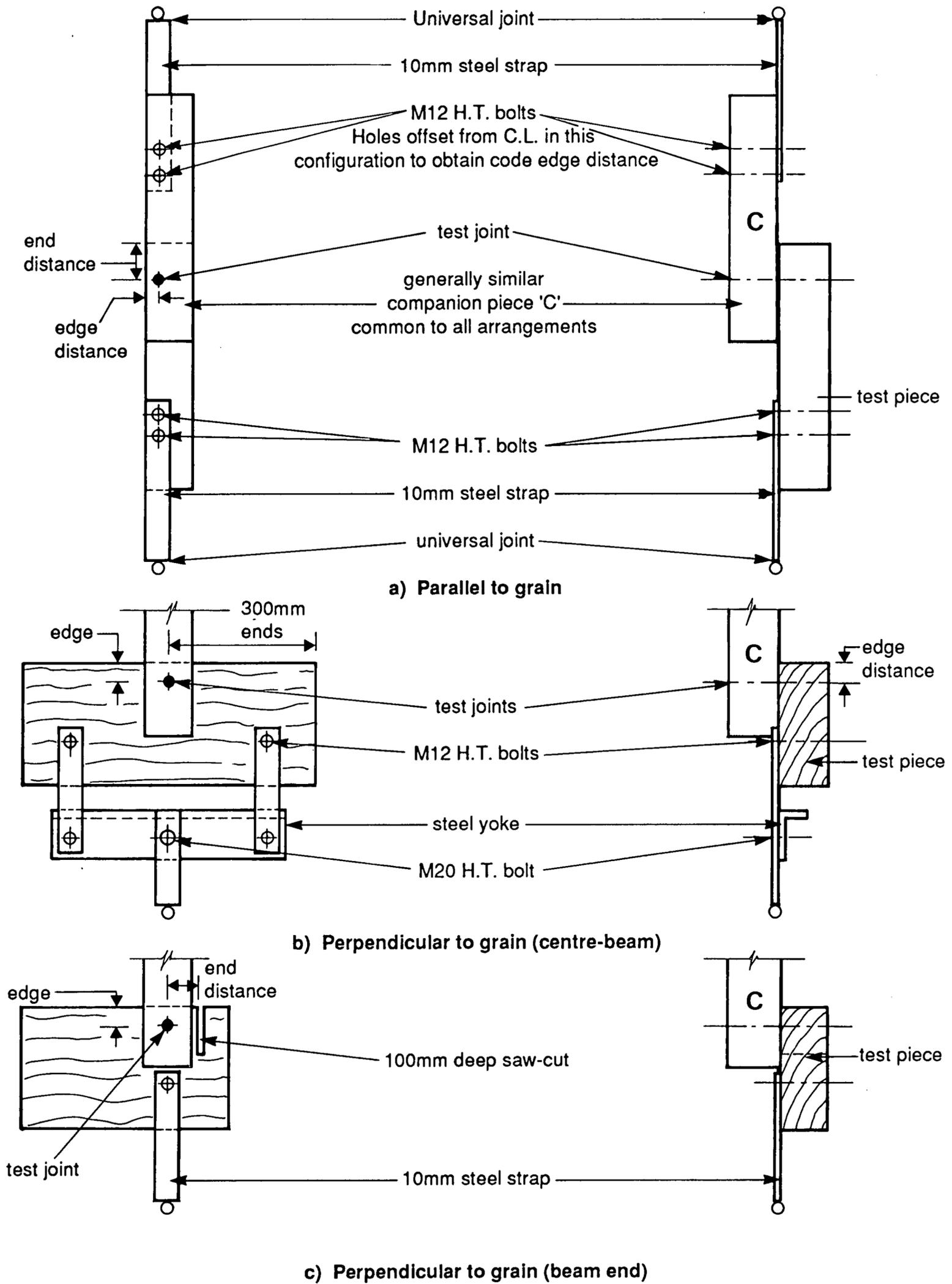


Figure 1 : General test arrangements

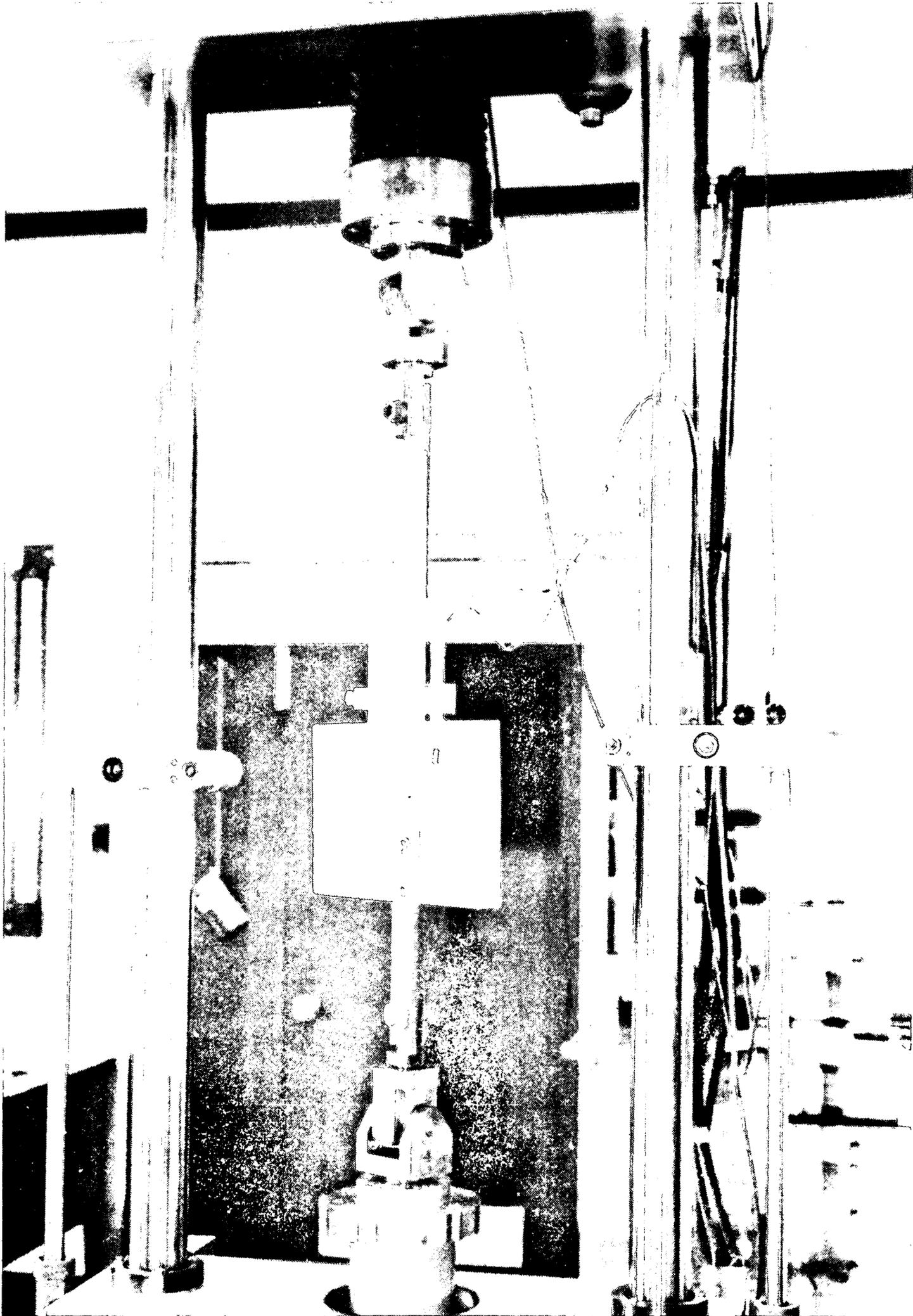


Figure 2 : Perpendicular to the grain short end distance specimen.

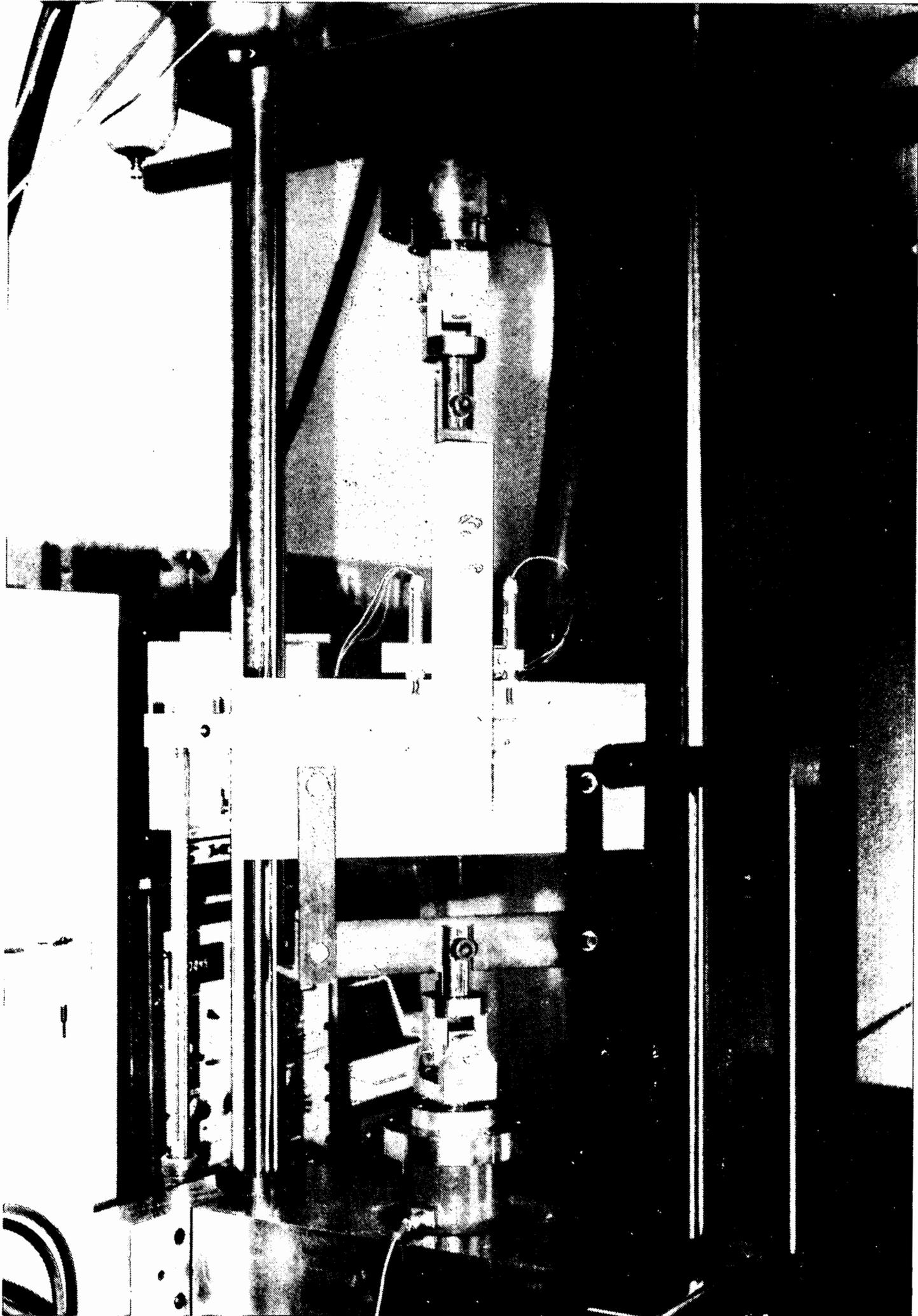


Figure 3 : Perpendicular to the grain mid-beam specimen.

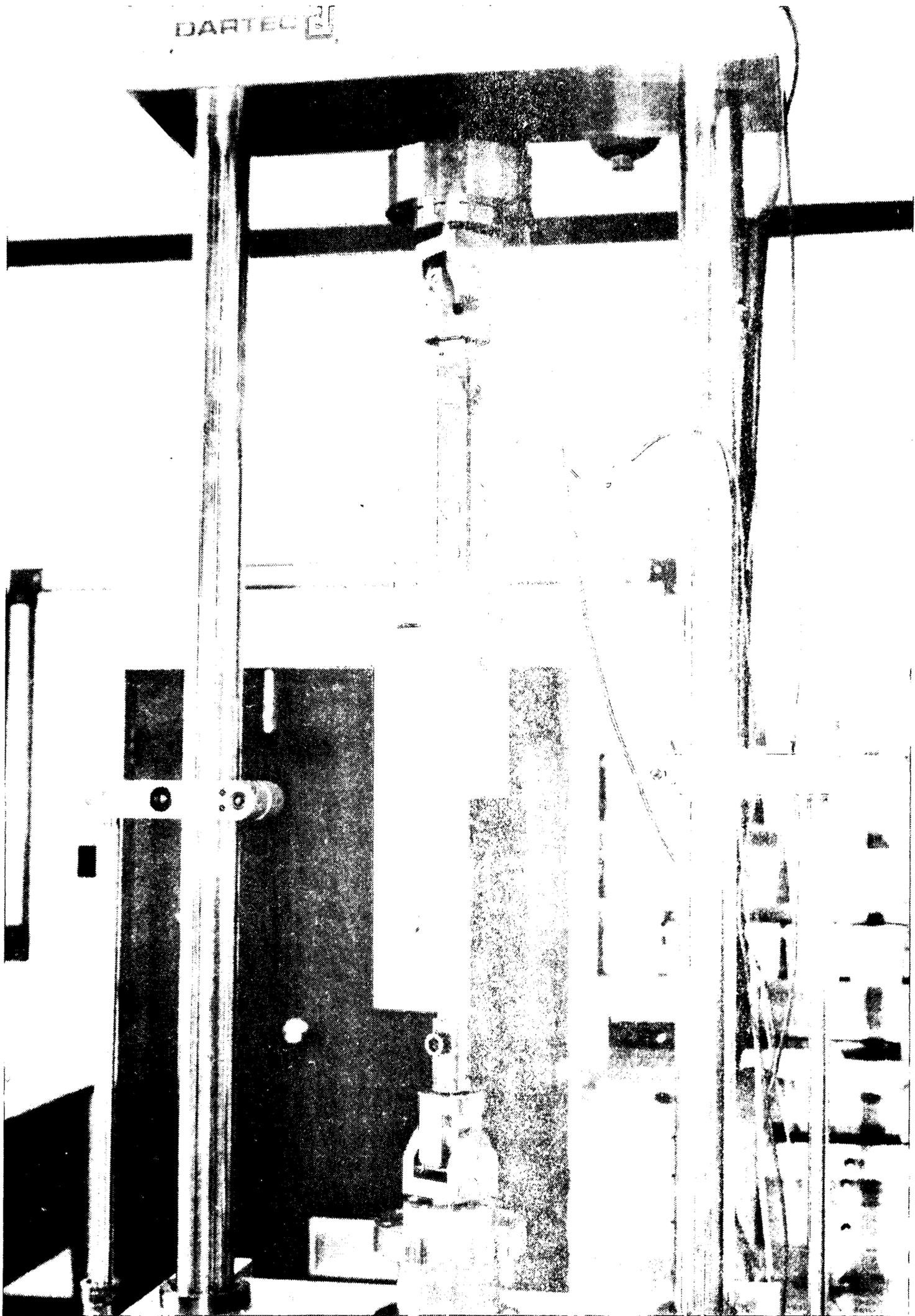


Figure 4 : Parallel to the grain specimen.

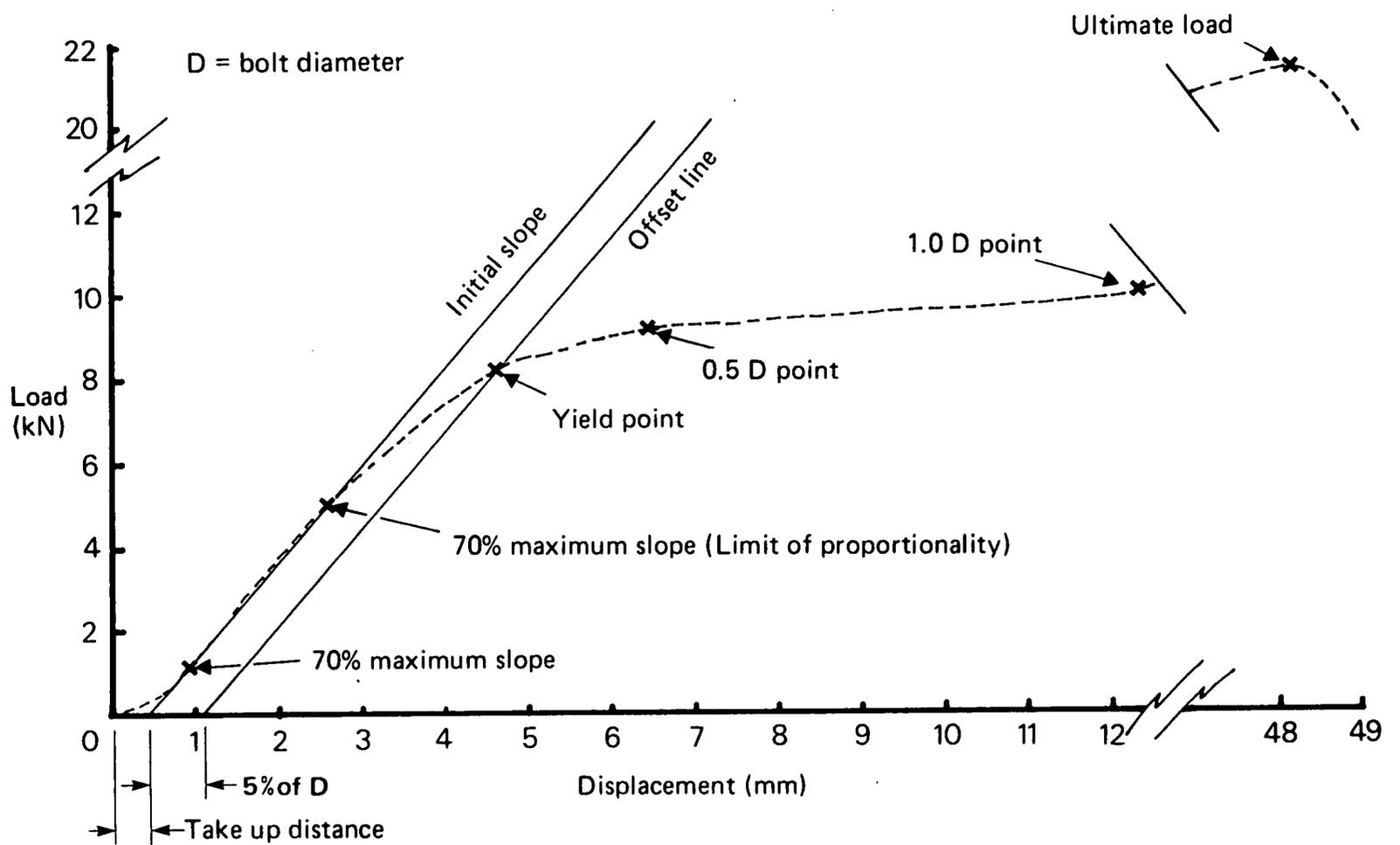
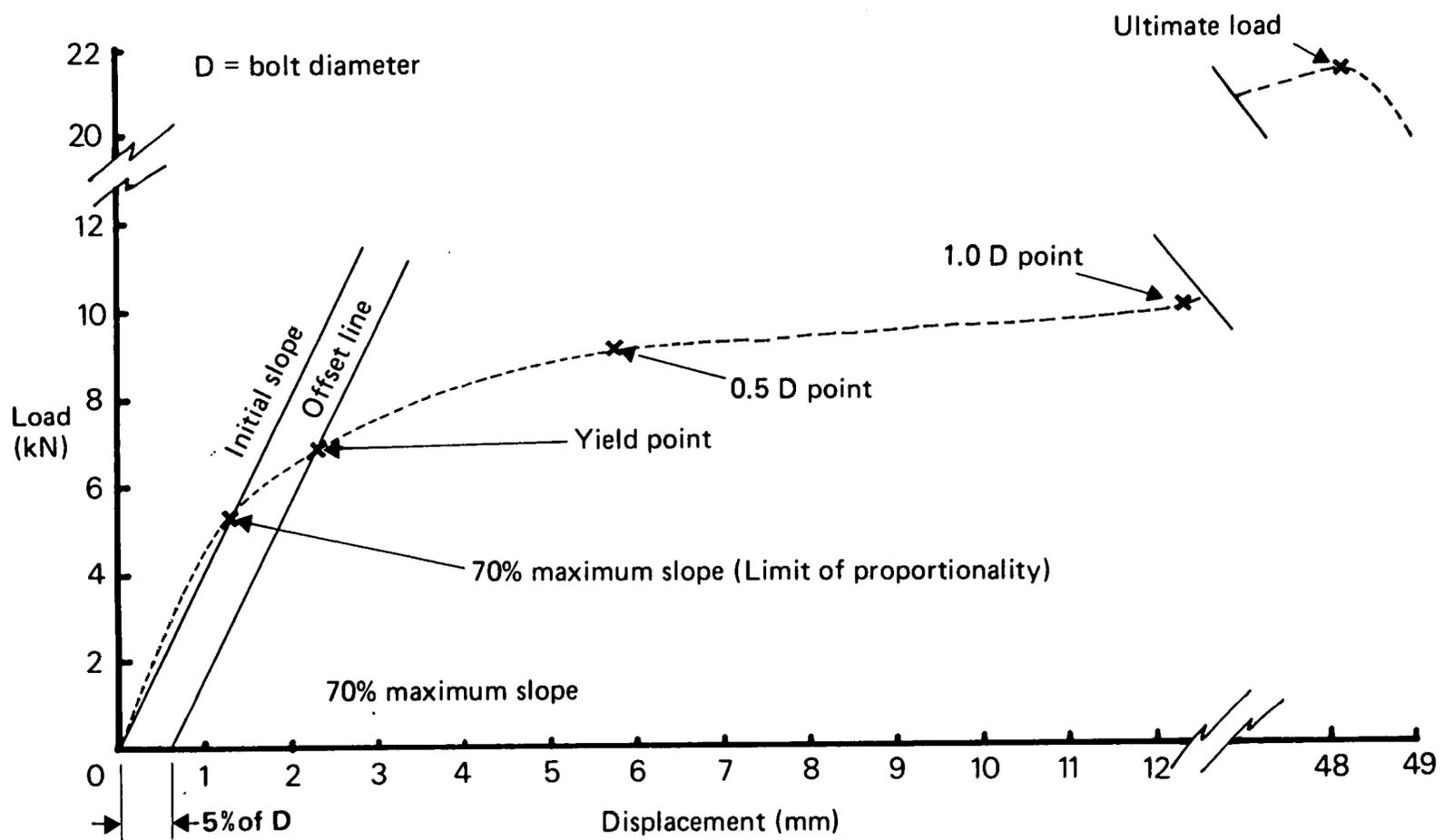


Figure 5 : Idealised load/displacement graph.

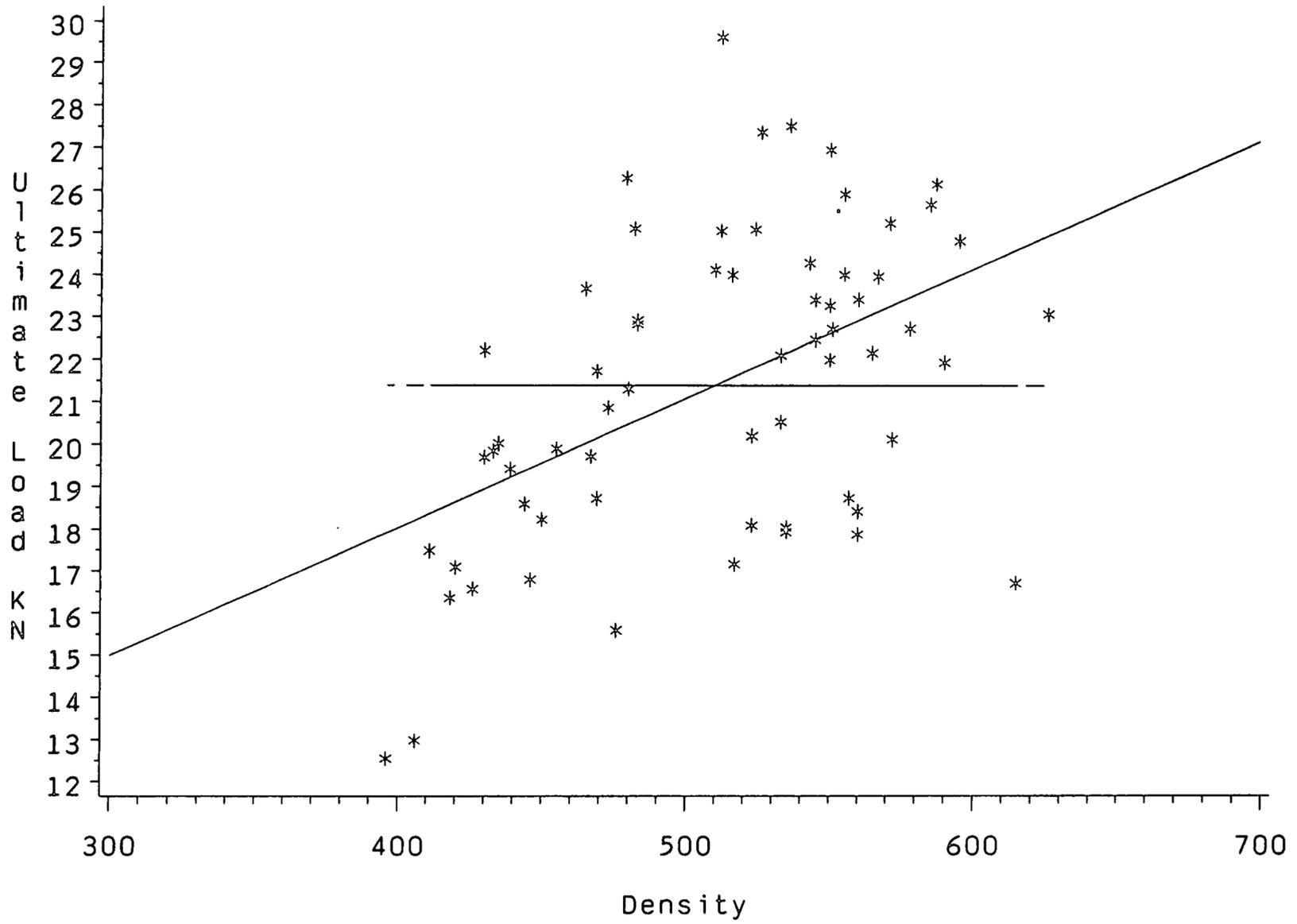


Figure 6 : Density effect for group c.

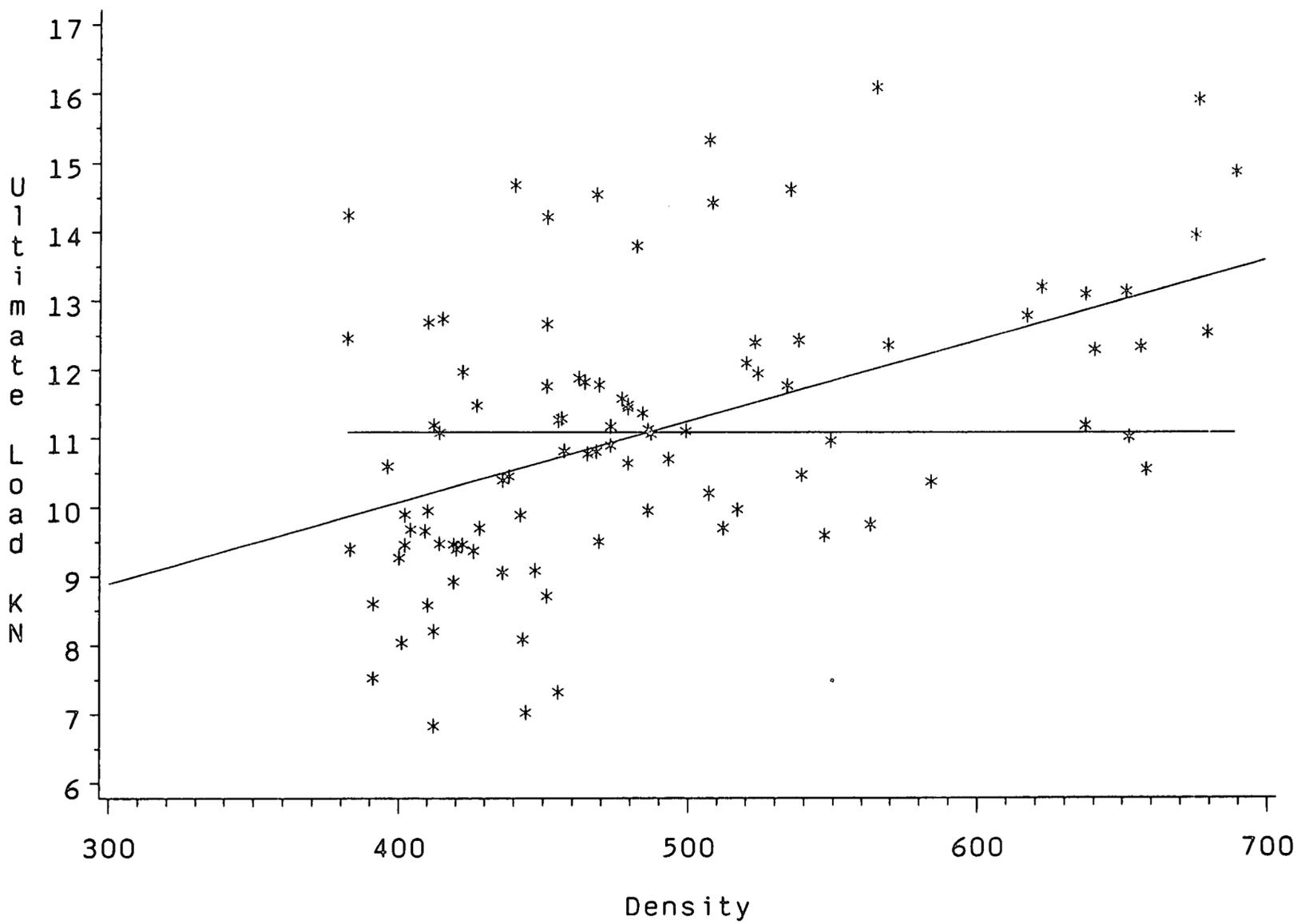


Figure 7 : Density effect for group f.

APPENDIX 1

Selection of Joint Variables and Combinations

SELECTION OF JOINT VARIABLES AND COMBINATIONS

This appendix gives the background and justification for the selection of the variables and combinations of variables incorporated in the test programme.

Variables

Bolt diameter and type

Consistent with the Stage 1 testing, hot-dip galvanised, hexagon-headed, mild steel 12mm diameter bolts (M12 bolts) manufactured by AJAX-Fasteners NZ Ltd were used for this programme.

As an additional variation 12mm coach bolts were included in the test programme and are specified under 'Washer size, Variation code C'.

Timber thickness, Variation code A

In the previous experimental work this was known as slenderness ratio, a term which caused unnecessary confusion.

The two timber thicknesses chosen for this programme, 50mm and 100mm nominal, are the minimum seen in the survey of the New Zealand building industry and an effective maximum with respect to any enhancement in strength for 12mm bolts.

Although the use of 75mm thick timber is also widespread, the difference in strength between 50mm and 100mm timbers found in Stage 1 does not warrant testing an intermediate timber thickness.

Bolt hole size, Variation code B

Two commonly available metric drill bit sizes of 13mm and 15mm were chosen. The smaller size produces a hole within the current Code allowable $D + 1.5\text{mm}$. The diameter of the larger hole is greater than what is commonly found in practice. These drill bit sizes differ from the Stage 1 imperial sizes of 13.5mm (17/32 inch) and 15.9mm (5/8 inch).

Washer size, Variation code C

50mm x 50mm square x 3mm thick and 32mm diameter x 3mm thick, hot-dip galvanised mild steel washers were used- the first being the NZS 3603 requirement and the latter a widely used practical minimum.

As an additional variation, hot-dip galvanised, cup head, square neck 12mm diameter mild steel bolts (Coach bolts) manufactured by AJAX-Fasteners NZ Ltd were incorporated in the test programme. These bolts are intended to be installed without a washer under the head and are commonly used in practice.

Edge distance, Variation code D

Parallel to the grain: The Code minimum of 2D has been used as in Stage 1 since no lesser distance was observed in practice.

Perpendicular to the grain: The 4D Code minimum was used as control with an edge distance of 2.5D as the variation which was observed as a practical minimum.

End distance, Variation code E

Parallel to the grain:

A control joint specification of 7D was selected, which is consistent with most overseas Code requirements. According to Harding (1982) the use of an 8D end distance in the Australian Code is to allow for the severe end splitting which occurs in Australian hardwoods on drying. *Pinus radiata* does not suffer this effect to the same extent. The minimum generally used end distance of 4D was adopted as an ultimate variation. An intermediate end distance of 5.5D has been included to check the end distance versus joint strength relationship. The 3D used in Stage 1 produced very low design values and is considered an unrealistic minimum.

Perpendicular to the grain:

The control joint specification for end distance has been taken as 300mm, which was, at the experimental design stage, considered remote from any end effects. The minimum end distance of 4D, given in overseas Codes, was adopted as a reasonable minimum. No intermediate value was incorporated in anticipation of research into the end effects by others.

Combinations of Variables

Subgroup: Parallel to the grain, assembled wet tested wet

Variation code:	Reason for inclusion:
O (Control)	To provide comparison with the Code
B (Large hole)	To confirm Stage 1 conclusion of no effect due to increased bolt hole size and to increase the number of control joint specimens. A large bolt hole is used in all other specimens because: <ul style="list-style-type: none"> a) No effect was found in Stage 1 b) Large holes are very often used in practice
BA (Large hole, Thin timber)	Timber thickness had an effect on ultimate load in Stage 1.
BC (Large hole, Small washer)	Small washers had an effect on 0.5D, 1.0D and ultimate loads in Stage 1.
BC1 (Large hole, Coach bolt)	A very common type joint seen in practice. The absence of a washer under the bolt head is expected to have an effect on joint performance.
BE (Large hole, Short end)	Short end distance had a significant effect in Stage 1.
BE1 (Large hole, Intermediate end)	An intermediate end distance was included to check for end distance versus joint strength relationship.
BAC (Large hole, Thin timber, Small washer)	Thin timber and small washers produced a large effect on loads up to 1.0D level in Stage 1. (However, this effect disappeared when allowance was made for density.)
BAE (Large hole, Thin timber, Short end)	Affected ultimate load in Stage 1.
BCE (Large hole, Small washer, Short end)	Affected ultimate load in Stage 1 less than would be predicted by adding the individual effects of the variations.
BACE (Large hole, Thin timber, Small washer, Short end)	Affected ultimate load in Stage 1.

Subgroups: Parallel to the grain, assembled wet tested dry
assembled dry tested dry

Variation code:	Reason for inclusion:
0 (A) (Control, Thin timber)	Comparison with the Code. Timber thickness had no effect in Stage 1 and was therefore used for all tests in this series.
B (A) (Large hole, Thin timber)	To confirm Stage 1 conclusion of no effect due to increased bolt hole size and to increase the number of control joint specimens. A large bolt hole is used in all other specimens because: a) No effect was found in Stage 1 b) Large holes are very often used in practice
BC (A) (Large hole, Small washer, Thin timber)	Small washers had an effect on ultimate load in Stage 1.
BC1 (A) (Large hole, Coach bolt, Thin timber)	A very common joint type seen in practice, not tested in Stage 1.
BE (A) (Large hole, Short end, Thin timber)	Short end distance had a significant effect on 1D and ultimate loads in Stage 1.
BE1 (A) (Large hole, Intermediate end, Thin timber)	An intermediate end distance was included to check for end distance versus joint strength relationship.
BCE (A) (Large hole, Small washer, Short end, Thin timber)	Affected proportional limit, yield and ultimate load in Stage 1.
BCE1 (A) (Large hole, Small washer, Intermediate end, Thin timber)	An intermediate end distance was not tested in Stage 1.

Subgroup: Perpendicular to the grain, assembled wet tested wet

Variation code:	Reason for inclusion:
0 (Control)	Comparison with the Code.
B (Large hole)	To confirm Stage 1 conclusion of no effect due to increased bolt hole size and to increase the number of control joint specimens. A large bolt hole is used in all other specimens because: <ul style="list-style-type: none"> a) No effect was found in Stage 1 b) Large holes are very often used in practice
BA (Large hole, Thin timber)	Timber thickness was included since it was part of the AD interaction in Stage 1.
BC (Large hole, Small washer)	Small washers had an effect on ultimate load in Stage 1.
BC1 (Large hole, Coach bolt)	A very common joint type seen in practice. Not tested in Stage 1.
BD (Large hole, Small edge)	Small edge had an effect on yield and ultimate load in Stage 1.
BE (Large hole, Short end)	Short end distance had a significant effect on ultimate loads in Stage 1.
BAD (Large hole, Thin timber, Small edge)	This combination had an effect on yield and ultimate loads in Stage 1.
BCE (Large hole, Small washer, Short end)	Small washers and small edge affected yield and ultimate loads in Stage 1.
BDE (Large hole, Small edge, Short end)	Affected yield load in Stage 1.

Subgroups: Perpendicular to the grain, assembled wet tested dry
assembled dry tested dry

Variation code:	Reason for inclusion:
0 (Control)	Comparison with the Code.
B (Large hole)	To confirm Stage 1 conclusion of no effect due to increased bolt hole size and to increase the number of control joint specimens. A large bolt hole is used in all other specimens because: <ul style="list-style-type: none"> a) No effect was found in Stage 1 b) Large holes are very often used in practice
BA (Large hole, Thin timber)	Timber thickness had an effect on proportional limit and yield displacement.
BC (Large hole, Small washer)	Small washers had an effect on prportional limit load and displacement and yield displacement in Stage 1.
BC1 (Large hole , Coach bolt)	A very common type joint seen in practice. Not tested in Stage 1.
BD (Large hole, Small edge)	Small edge had an effect on ultimate load in Stage 1.
BE (Large hole, Short end)	Short end distance had a significant effect on ultimate loads in Stage 1.
BAC (Large hole, Thin timber, Small washer)	This combination had an effect on proportional limit load and displacement and yield displacement in Stage 1.
BCE (Large hole, Small washer, Short end)	Small washers and small edge affected proportional limit loads in Stage 1.
BDE (Large hole, Small edge, Short end)	Affected slope generally and ultimate displacement in Stage 1.

APPENDIX 2

Density Conversions

Density conversion for New Zealand Pine in accordance with Collins (1983).

Dod (oven-dry density) = W_o/V_o (oven-dry weight/ oven-dry volume)

Db (basic density) = W_o/V_{30} (oven-dry weight/ green volume)

$$\text{So: } V_o = D_b \times V_{30} / D_{od} \quad (1)$$

Relationship between V_o and V_{30} :

$$V_o = V_{30} - (S \times V_{30}/100)$$

$$S = 0.017 D_b + 4.7 \text{ (NZ Pine sapwood)}$$

$$\text{So: } V_o = V_{30} - (0.017 D_b + 4.7) V_{30}/100 \quad (2)$$

From (1) and (2):

$$D_b \times V_{30} / D_{od} = V_{30} - (0.017 D_b + 4.7) V_{30}/100 \quad \text{or,}$$

$$D_b = D_{od} - (0.017 D_b + 4.7) D_{od}/100$$

Conversions tabulated:

Dod	Db		Dod	Db	
380	340	kg/ m ³	520	455	kg/ m ³
390	349	kg/ m ³	530	463	kg/ m ³
400	357	kg/ m ³	540	471	kg/ m ³
410	365	kg/ m ³	550	479	kg/ m ³
420	374	kg/ m ³	560	487	kg/ m ³
430	382	kg/ m ³	570	495	kg/ m ³
440	390	kg/ m ³	580	503	kg/ m ³
450	398	kg/ m ³	590	511	kg/ m ³
460	407	kg/ m ³	600	519	kg/ m ³
470	415	kg/ m ³	610	527	kg/ m ³
480	423	kg/ m ³	620	534	kg/ m ³
490	431	kg/ m ³	630	542	kg/ m ³
500	439	kg/ m ³	640	550	kg/ m ³
510	447	kg/ m ³	650	558	kg/ m ³

APPENDIX 3**Raw Data**

MC = Moisture Content

Dens = Density

PLL = Proportional Limit Load

PLD = Proportional Limit Displacement

YLL = Yield Load

YLD = Yield Displacement

TUP + 0.5D = Take-up + 0.5 x Bolt Diameter

TUP + 1.0D = Take-up + 1.0 x Bolt Diameter

ULTL = Ultimate Load

ULTD = Ultimate Displacement

Group A - Parallel to grain, constructed wet, tested wet

Means(standard deviations) of all measured variables by joint type

Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
aO	55.1(19.0)	499(32)	4.21(0.75)	0.24(0.20)	4.87(1.11)	0.74(0.05)	11.19(1.33)	13.23(1.52)	23.07(4.90)	54.03(17.1)
aB	55.8(9.3)	467(40)	3.97(0.52)	0.16(0.05)	5.07(0.88)	0.75(0.04)	10.17(1.08)	12.06(1.21)	20.86(2.85)	63.14(14.5)
aBA	84.1(17.0)	498(22)	4.57(0.50)	0.12(0.05)	5.47(0.84)	0.73(0.02)	10.20(0.75)	12.22(0.60)	22.74(4.65)	47.90(9.48)
aBC	62.4(13.9)	464(44)	2.43(0.81)	0.19(0.10)	2.74(1.16)	0.71(0.05)	7.44(1.38)	9.28(1.24)	19.11(3.56)	62.89(8.56)
aBC1	56.3(20.2)	477(67)	2.91(1.24)	0.22(0.12)	4.14(1.37)	0.87(0.13)	9.06(1.99)	10.65(2.55)	19.78(6.19)	56.56(13.6)
aBE	53.3(25.3)	495(56)	3.80(1.26)	0.13(0.06)	5.66(2.06)	0.81(0.11)	10.55(2.15)	12.54(2.87)	16.69(4.08)	36.53(11.3)
aBE1	48.8(16.8)	468(27)	3.65(0.71)	0.17(0.11)	4.88(1.09)	0.80(0.07)	9.99(1.54)	11.53(1.63)	16.68(2.42)	45.45(10.4)
aBAC	81.0(19.1)	519(32)	2.54(0.30)	0.10(0.05)	3.25(0.43)	0.70(0.04)	8.01(0.81)	10.34(0.90)	20.46(2.09)	44.56(5.02)
aBAC1	92.4(12.4)	488(30)	2.38(0.38)	0.16(0.03)	3.03(0.43)	0.74(0.04)	7.73(0.83)	9.63(0.86)	14.84(1.93)	34.53(3.24)
aBAE	82.3(18.8)	527(31)	4.38(0.88)	0.11(0.04)	5.45(0.49)	0.72(0.05)	10.90(0.75)	12.77(0.93)	14.23(0.92)	20.21(5.87)
aBCE	66.9(14.0)	450(29)	1.85(0.20)	0.17(0.08)	2.61(0.73)	0.75(0.07)	7.13(0.89)	8.28(0.71)	11.31(2.33)	32.19(14.4)
aBACE	83.0(22.5)	522(46)	2.15(0.58)	0.22(0.21)	3.63(1.21)	0.73(0.03)	7.35(1.09)	9.27(1.33)	10.53(1.72)	16.93(5.01)

Group B - Parallel to grain, constructed wet, tested dry

Means(standard deviations) of all measured variables by joint type

Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
bA	14.2(0.4)	541(40)	7.88(1.47)	3.31(0.70)	13.52(0.89)	5.85(0.91)	14.88(0.69)	17.79(0.74)	30.06(4.93)	39.81(10.6)
bAB	14.7(0.5)	537(28)	8.50(2.07)	4.56(1.51)	12.24(2.06)	6.82(1.48)	12.66(0.96)	16.30(0.90)	30.53(5.81)	43.75(12.5)
bABC	15.0(0.6)	503(34)	7.00(1.19)	4.38(1.30)	10.26(1.54)	6.64(1.58)	10.78(1.94)	14.29(1.76)	22.82(5.12)	38.70(18.2)
bABC1	14.8(0.6)	524(39)	7.83(1.11)	5.98(0.63)	11.32(1.05)	8.56(0.77)	10.68(1.01)	13.70(1.03)	21.62(4.33)	33.49(12.8)
bABE	14.2(0.7)	510(40)	8.27(2.12)	4.46(1.14)	11.89(1.65)	6.49(1.26)	12.40(2.23)	14.40(1.90)	16.10(2.89)	15.06(7.13)
bABE1	14.6(0.6)	529(55)	9.37(2.09)	5.29(1.73)	12.53(1.15)	7.34(1.69)	12.54(1.39)	16.06(0.64)	23.44(4.02)	32.28(12.2)
bABCE	14.3(0.4)	534(35)	7.23(1.72)	6.17(2.33)	10.54(1.43)	8.12(2.64)	11.84(1.61)	15.07(2.65)	14.94(2.30)	13.73(3.39)
bABCE1	14.5(0.7)	493(16)	7.39(0.79)	4.92(1.17)	10.54(0.77)	7.15(1.25)	11.15(0.91)	14.09(1.19)	18.98(2.63)	29.62(3.07)

Group C - Parallel to grain, constructed dry, tested dry

Means(standard deviations) of all measured variables by joint type

Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
cA	15.0(1.4)	506(46)	3.77(0.82)	0.08(0.04)	4.71(0.95)	0.80(0.08)	12.99(1.59)	15.77(1.80)	27.12(4.22)	41.18(8.43)
cAB	14.9(1.4)	496(67)	4.63(1.25)	0.11(0.07)	6.15(1.26)	0.76(0.10)	13.55(2.37)	16.02(2.77)	28.20(3.14)	44.08(9.73)
cABC	15.7(1.7)	504(66)	2.65(0.82)	0.10(0.05)	4.54(1.56)	0.74(0.04)	11.07(2.45)	13.57(2.59)	21.07(4.03)	36.90(12.9)
cABC1	15.5(1.6)	493(34)	2.78(0.79)	0.18(0.10)	3.87(1.20)	0.80(0.13)	9.27(2.89)	12.80(2.84)	19.15(4.27)	30.37(7.44)
cABE	15.2(1.9)	505(59)	3.21(1.25)	0.08(0.04)	4.60(1.44)	0.76(0.02)	11.87(2.02)	14.51(2.89)	18.05(3.17)	19.39(3.11)
cABE1	15.2(1.7)	510(63)	4.09(0.87)	0.09(0.05)	5.94(1.23)	0.73(0.02)	14.08(1.34)	16.52(1.59)	24.70(4.94)	31.73(6.79)
cABCE	15.6(1.5)	526(72)	2.34(0.93)	0.15(0.07)	3.52(1.38)	0.79(0.05)	9.90(3.94)	13.05(2.84)	15.11(2.80)	17.34(3.23)
cABCE1	14.8(1.9)	539(59)	2.81(0.76)	0.15(0.11)	4.22(1.31)	0.79(0.12)	10.19(1.72)	13.18(2.20)	17.78(3.68)	25.76(9.06)

Group D - Perpendicular to grain, constructed wet, tested wet

Means(standard deviations) of all measured variables by joint type

Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
dO	38.3(9.8)	456(57)	2.66(0.97)	0.13(0.05)	4.64(1.29)	0.92(0.08)	9.19(1.58)	11.16(1.20)	12.00(2.15)	15.23(5.92)
dB	38.6(9.7)	446(68)	3.34(0.82)	0.17(0.04)	5.20(1.03)	0.97(0.09)	8.86(1.29)	11.53(1.20)	12.53(1.18)	16.71(4.45)
dBa	56.6(26.8)	458(30)	3.29(1.02)	0.17(0.05)	5.52(0.64)	0.95(0.06)	8.67(1.81)	10.80(0.69)	11.50(1.62)	15.85(6.99)
dBc	37.8(7.6)	466(70)	1.65(0.43)	0.11(0.04)	2.15(0.59)	0.78(0.13)	5.19(1.69)	7.90(0.88)	10.10(1.29)	22.64(7.63)
dBc1	35.6(10.1)	452(67)	1.76(0.44)	0.19(0.22)	2.31(0.65)	0.82(0.10)	6.63(1.20)	8.96(0.84)	9.81(0.97)	16.38(4.30)
dBd	38.3(6.4)	459(47)	2.46(0.82)	0.15(0.04)	4.76(1.65)	1.02(0.15)	7.50(2.68)	8.83(1.10)	9.85(0.86)	12.44(7.48)
dBe	33.5(14.9)	495(79)	2.61(0.66)	0.26(0.12)	4.09(1.28)	1.22(0.14)	5.60(0.47)	.(.)	6.70(1.40)	5.78(2.69)
dBAC1	38.5(6.5)	484(37)	1.58(0.31)	0.14(0.05)	2.52(0.44)	0.91(0.12)	5.50(1.41)	7.39(1.20)	8.73(1.60)	16.78(6.30)
dBAD	36.3(14.3)	513(48)	2.31(0.84)	0.26(0.07)	3.80(1.77)	1.11(0.28)	5.98(2.90)	8.72(1.38)	9.08(1.21)	11.33(3.89)
dBCE	29.3(6.8)	433(50)	1.59(0.37)	0.17(0.09)	2.05(0.60)	0.96(0.14)	4.49(0.47)	.(.)	5.23(0.76)	8.25(1.44)
dBc1E	30.3(9.4)	468(56)	1.50(0.23)	0.17(0.05)	2.13(0.46)	1.06(0.12)	4.47(1.81)	4.90(.)	5.45(1.26)	8.65(3.62)
dBDE	28.5(8.3)	460(44)	2.55(1.09)	0.30(0.11)	4.66(1.65)	1.37(0.28)	7.30(.)	.(.)	5.90(1.38)	3.34(1.55)

Group E - Perpendicular to grain, constructed wet, tested dry

Means(standard deviations) of all measured variables by joint type

Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
eO	15.0(0.6)	459(52)	3.59(0.57)	1.85(0.49)	7.26(0.45)	4.69(0.52)	8.12(0.51)	10.01(0.78)	15.59(4.71)	21.72(7.51)
eB	14.4(1.1)	491(50)	4.25(1.30)	2.56(1.05)	8.58(0.54)	6.07(1.04)	8.54(0.85)	11.07(0.88)	14.83(3.51)	19.57(7.49)
eBA	16.6(0.6)	501(51)	7.26(1.21)	5.12(1.03)	10.56(1.04)	8.21(0.95)	9.00(1.14)	13.28(1.63)	13.23(2.65)	13.91(3.74)
eBC	14.3(1.0)	440(51)	4.06(1.08)	2.21(0.72)	7.32(0.73)	5.16(0.69)	7.98(0.79)	10.27(0.96)	13.47(2.44)	20.36(4.24)
eBC1	14.4(0.6)	493(63)	4.11(0.89)	2.54(0.91)	7.57(0.74)	5.65(1.03)	7.79(0.85)	10.09(0.90)	13.79(2.98)	20.54(6.58)
eBD	14.8(0.6)	463(34)	3.99(0.98)	2.95(0.66)	6.93(0.85)	6.23(0.83)	6.83(0.59)	8.85(0.53)	8.69(0.77)	12.37(2.96)
eBE	15.6(0.6)	528(58)	4.31(1.30)	2.96(1.23)	7.59(0.97)	5.71(1.96)	7.10(1.65)	.(.)	8.17(1.02)	7.22(3.37)
eBAC	16.8(0.5)	501(36)	5.10(1.43)	3.71(1.45)	8.31(0.99)	7.01(1.27)	7.50(0.78)	10.44(1.30)	11.70(2.22)	15.60(4.85)
eBAC1	17.3(0.5)	487(45)	5.00(1.75)	5.06(1.71)	7.74(2.05)	8.34(1.57)	6.70(1.45)	9.63(2.00)	11.69(2.31)	19.29(3.00)
eBCE	15.6(0.8)	495(59)	4.53(0.43)	3.83(0.79)	7.19(0.72)	6.70(1.54)	7.13(0.63)	.(.)	7.63(0.77)	7.36(1.46)
eBC1E	15.3(0.4)	487(47)	4.48(1.44)	3.56(0.91)	6.97(1.20)	5.90(1.15)	7.59(1.07)	.(.)	7.53(1.54)	7.68(2.52)
eBDE	15.5(0.7)	472(72)	4.05(1.40)	3.05(1.53)	6.72(0.80)	5.53(1.25)	6.67(1.01)	.(.)	6.97(0.75)	5.85(1.15)

Group F - Perpendicular to grain, constructed dry, tested dry
Means(standard deviations) of all measured variables by joint type

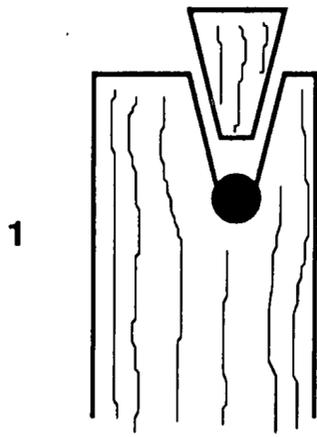
Joint Code	MC	DENS	PLL	PLD	YLL	YLD	TUP+0.5D	TUP+1.0D	ULTL	ULTD
fo	15.9(0.9)	475(65)	3.98(1.22)	0.12(0.05)	7.37(1.39)	0.89(0.13)	11.12(1.52)	14.04(1.43)	15.10(2.26)	14.20(6.10)
fb	17.1(1.4)	477(**)	3.48(1.62)	0.12(0.10)	6.86(1.50)	0.89(0.16)	12.09(1.19)	14.66(1.98)	16.49(3.35)	16.53(4.71)
fbA	14.9(1.2)	487(41)	4.54(2.06)	0.24(0.14)	8.09(1.02)	1.33(0.04)	11.08(1.27)	14.30(.)	11.18(2.58)	9.43(3.87)
fbC	16.8(1.0)	482(78)	2.96(0.63)	0.21(0.12)	4.81(1.77)	0.88(0.35)	9.58(1.75)	10.19(0.30)	12.25(2.13)	13.78(6.55)
fbC1	16.4(1.0)	447(54)	2.40(0.34)	0.16(0.11)	3.74(0.66)	0.86(0.22)	8.89(1.07)	11.09(1.04)	12.79(2.37)	17.68(6.07)
fbD	17.2(1.1)	511(96)	3.47(0.91)	0.20(0.11)	5.88(1.37)	0.94(0.14)	10.71(1.40)	11.57(0.91)	11.45(1.49)	9.48(4.35)
fbE	15.3(1.0)	518(95)	3.08(1.04)	0.16(0.08)	6.24(1.35)	0.98(0.13)	9.92(1.95)	12.90(.)	10.32(2.76)	6.70(4.59)
fbAC	14.5(1.3)	471(42)	4.39(0.88)	0.23(0.02)	6.01(1.00)	1.09(0.12)	8.66(0.86)	11.00(.)	9.83(1.54)	12.15(4.33)
fbAC1	14.7(1.1)	460(32)	2.73(0.75)	0.14(0.05)	4.56(0.69)	1.05(0.14)	7.80(0.55)	9.75(1.06)	9.28(0.97)	13.19(3.21)
fbCE	16.4(1.0)	502(98)	2.47(0.91)	0.21(0.10)	3.79(1.24)	0.93(0.09)	8.49(0.84)	.(.)	8.29(1.22)	5.75(1.46)
fbC1E	16.4(1.1)	516(**)	2.29(0.92)	0.23(0.10)	3.78(1.33)	1.03(0.20)	6.93(3.87)	.(.)	8.71(1.91)	7.23(2.85)
fbDE	16.0(2.1)	487(**)	3.18(1.12)	0.23(0.11)	5.70(0.97)	1.03(0.14)	.(.)	.(.)	7.47(1.38)	2.79(1.37)

** standard deviation greater than 99

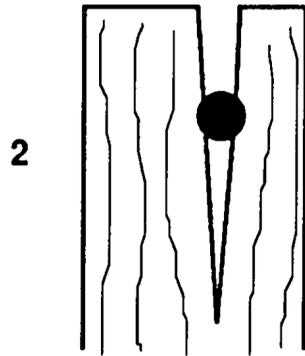
APPENDIX 4
Failure Modes

FAILURE MODES

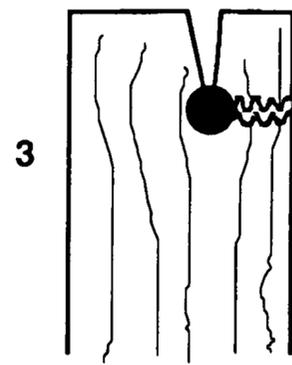
a, b, c PARALLEL TO THE GRAIN



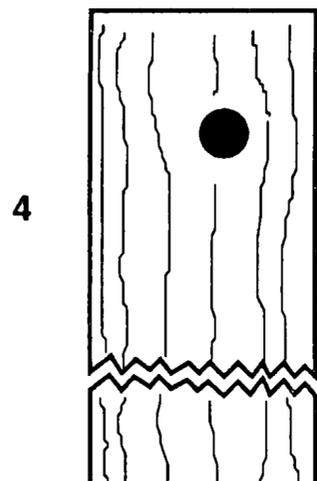
Shear key



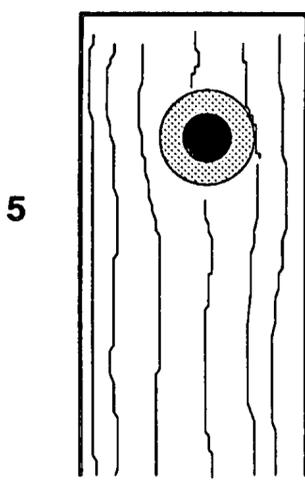
Split



Split and edge fracture

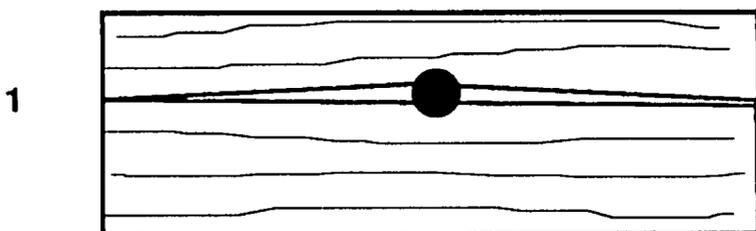


Fracture outside joint

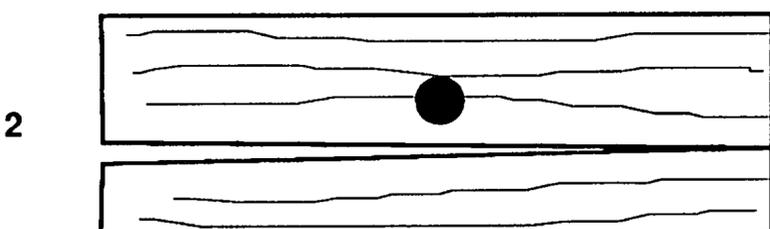


Crushing under head/washer

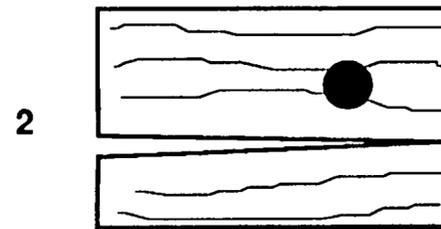
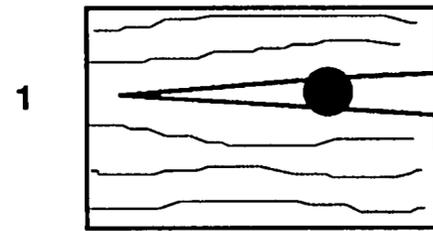
d, e, f PERPENDICULAR TO THE GRAIN



Split through joint



Fracture below joint



APPENDIX 5
Significant Effects

Group e. Perpendicular to the grain assembled wet tested dry

VARIABLES	LOAD AND DISPLACEMENT LEVELS							
	PROP. load	LIMIT displ	YIELD		0.5D load	1.0D load	ULTIMATE	
Control Mean	3.9kN	2.2mm	load 7.9kN	displ 5.4mm	8.3kN	10.6mm	load 15.2kN	displ 20.6mm
B			118#	128		*		
A	188++	243++	134	154++		*		69
C	++	+		+		*		
C1						*		
D		139#++			82	*	59++	62+
E					84#	*	55++	33++
Combinations:								
AC	128#					*		
AC1	123#		96		79	*		
CE			++			*		
C1E						*		
DE						*	47++	

Group f. Perpendicular to the grain assembled dry tested dry

VARIABLES	LOAD AND DISPLACEMENT LEVELS							
	PROP. load	LIMIT displ	YIELD		0.5D load	1.0D load	ULTIMATE	
Control Mean	3.7kN	0.1mm	load 7.1kN	displ 0.9mm	11.6kN	14.3mm	load 15.8kN	displ 15.4mm
B					*	*		
A					*	*	69	59
C			65		*	*	77	
C1	68#		53		*	*	84#	
D					*	*	70	57
E					*	*	61	33
Density					*	*	100.1	100.2
Combinations:								
AC					*	*		
AC1					*	*		
CE					*	*		
C1E					*	*		
DE					*	*		

APPENDIX 6

Load Displacement Graphs

Graph:

P = Proportional Limit

Y = Yield

D = Take-up + (0.5 or 1.0) x Bolt Diameter

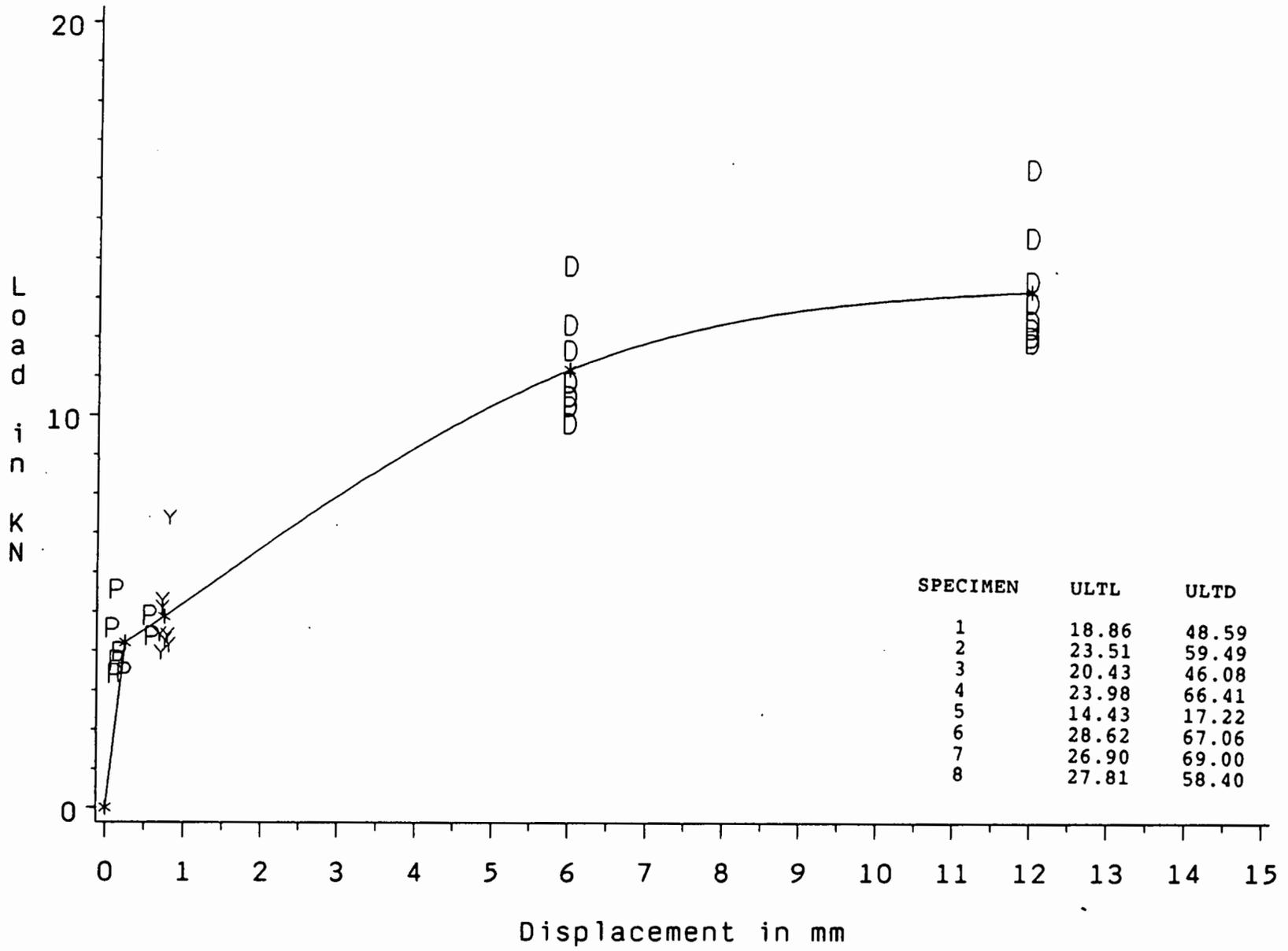
U = Ultimate

Table:

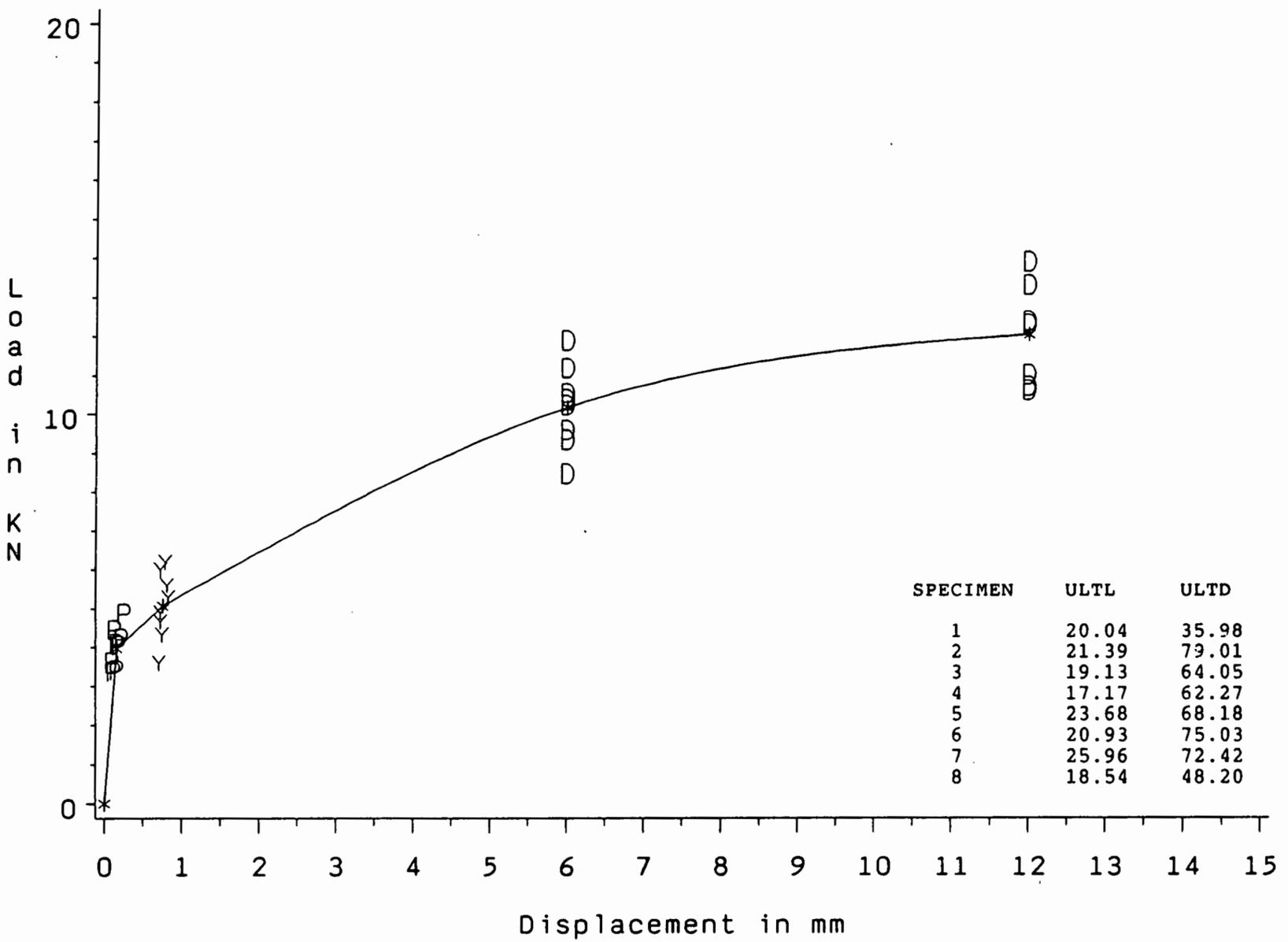
ULTL = Ultimate Load

ULTD = Ultimate Displacement

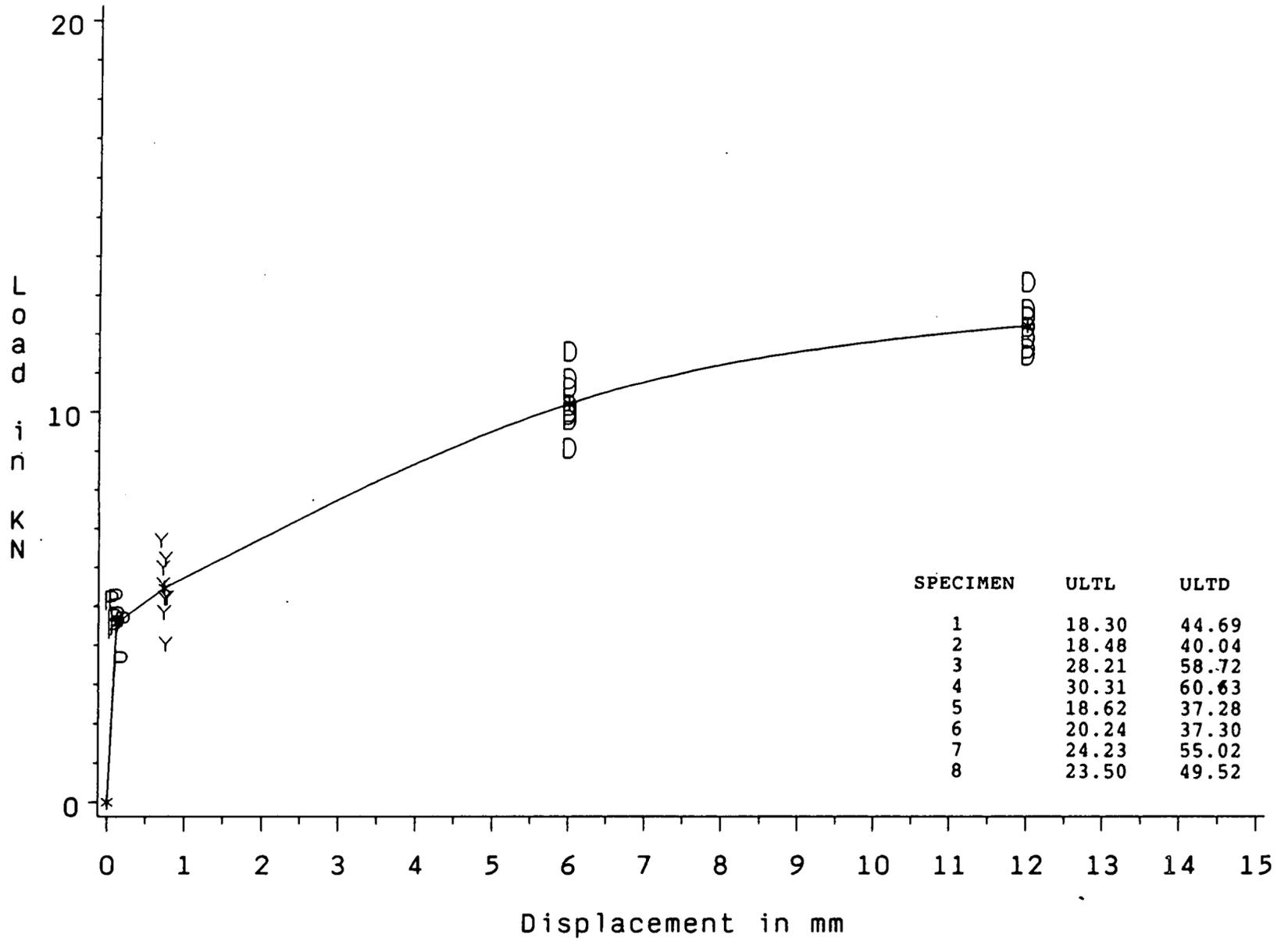
Joint code=a0



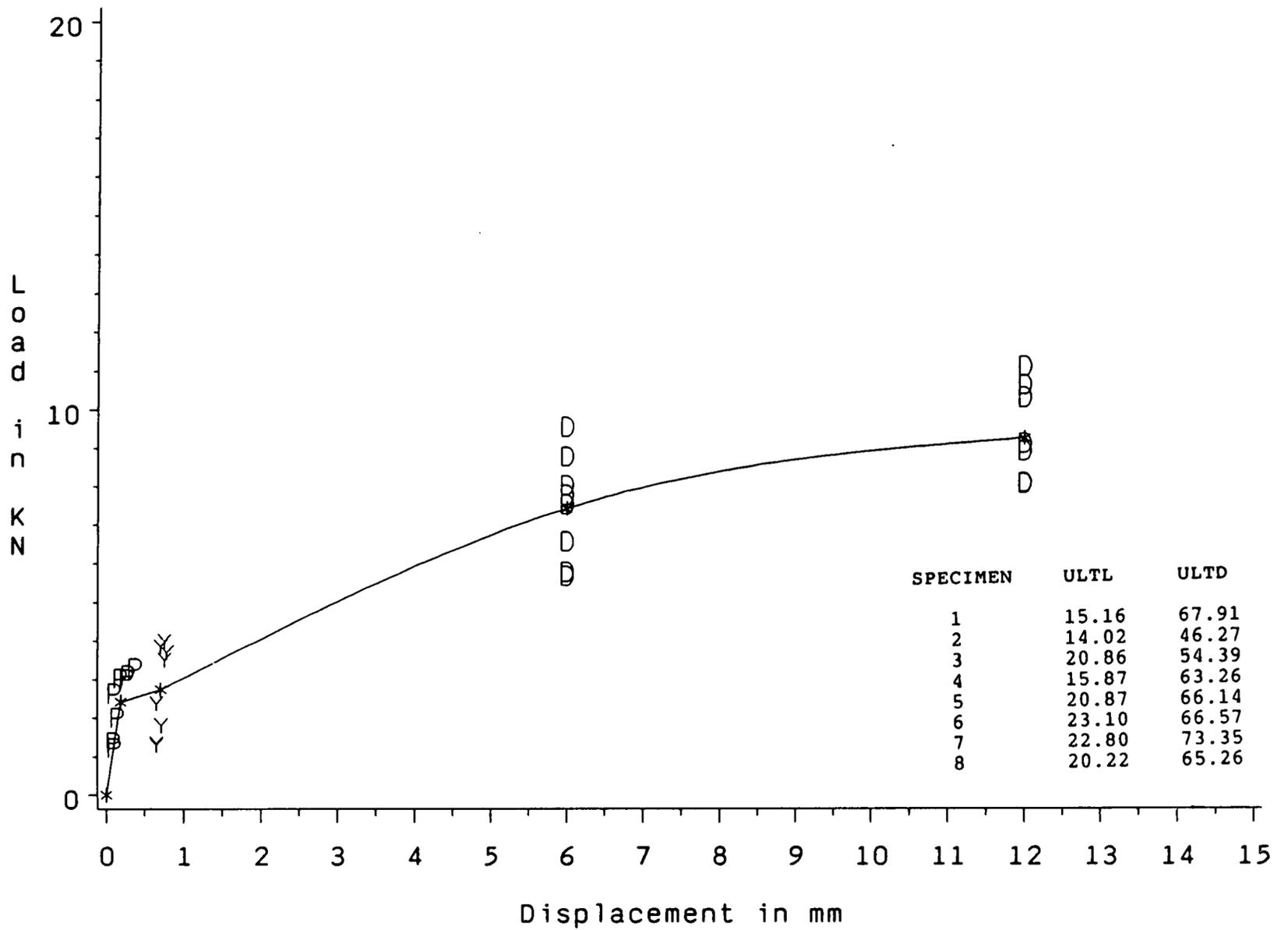
Joint code=aB



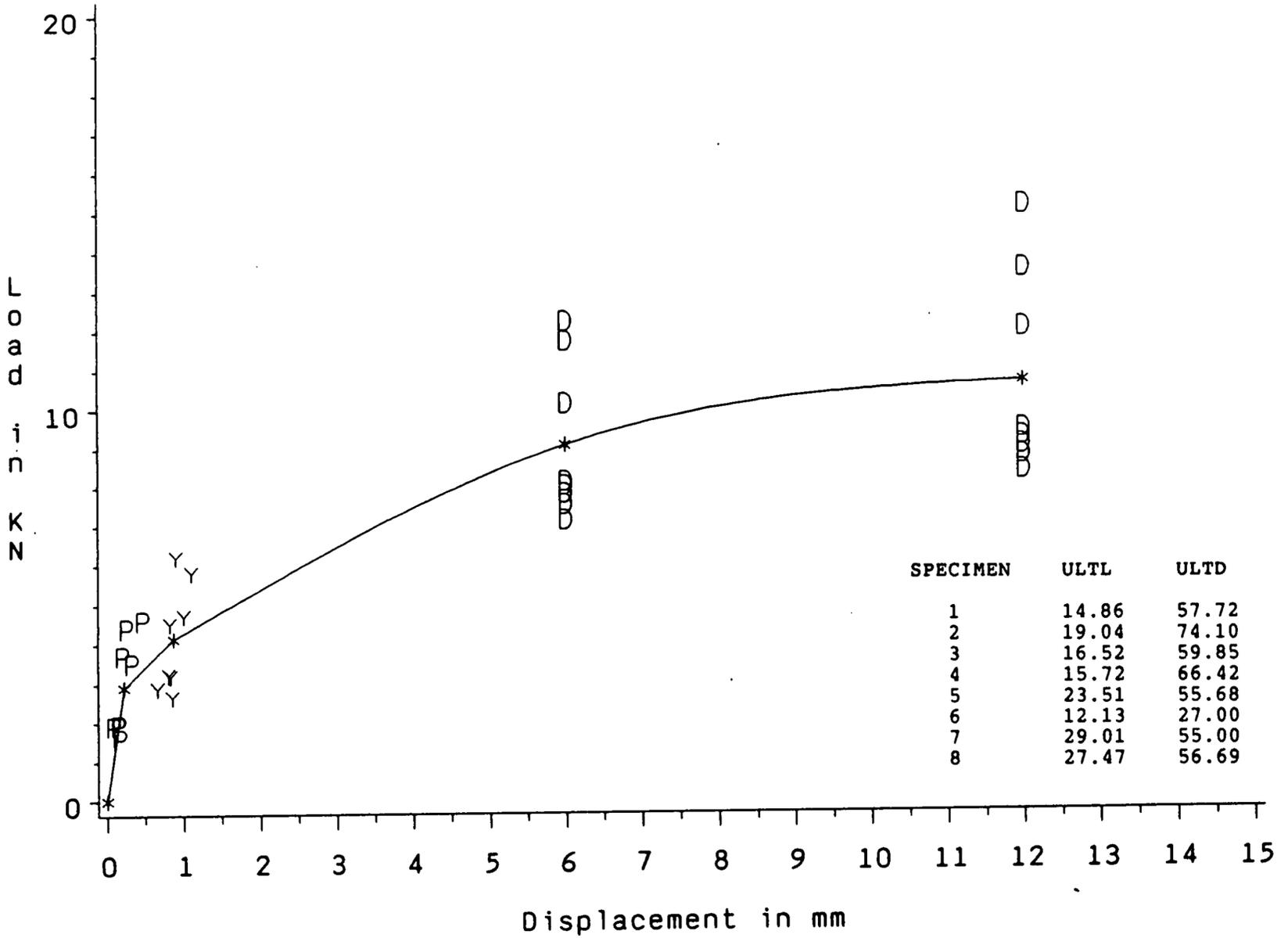
Joint code=aBA



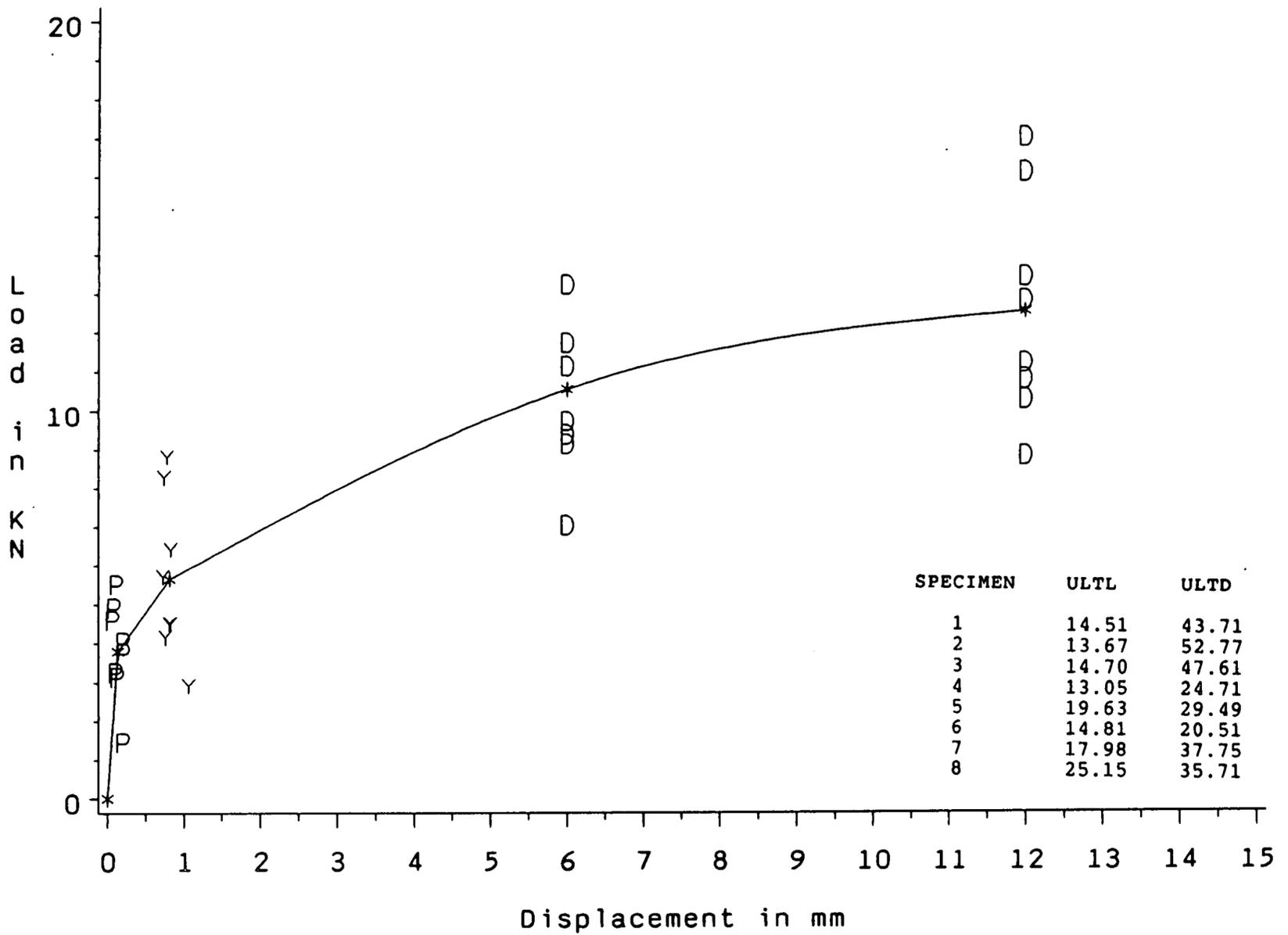
Joint code=aBC



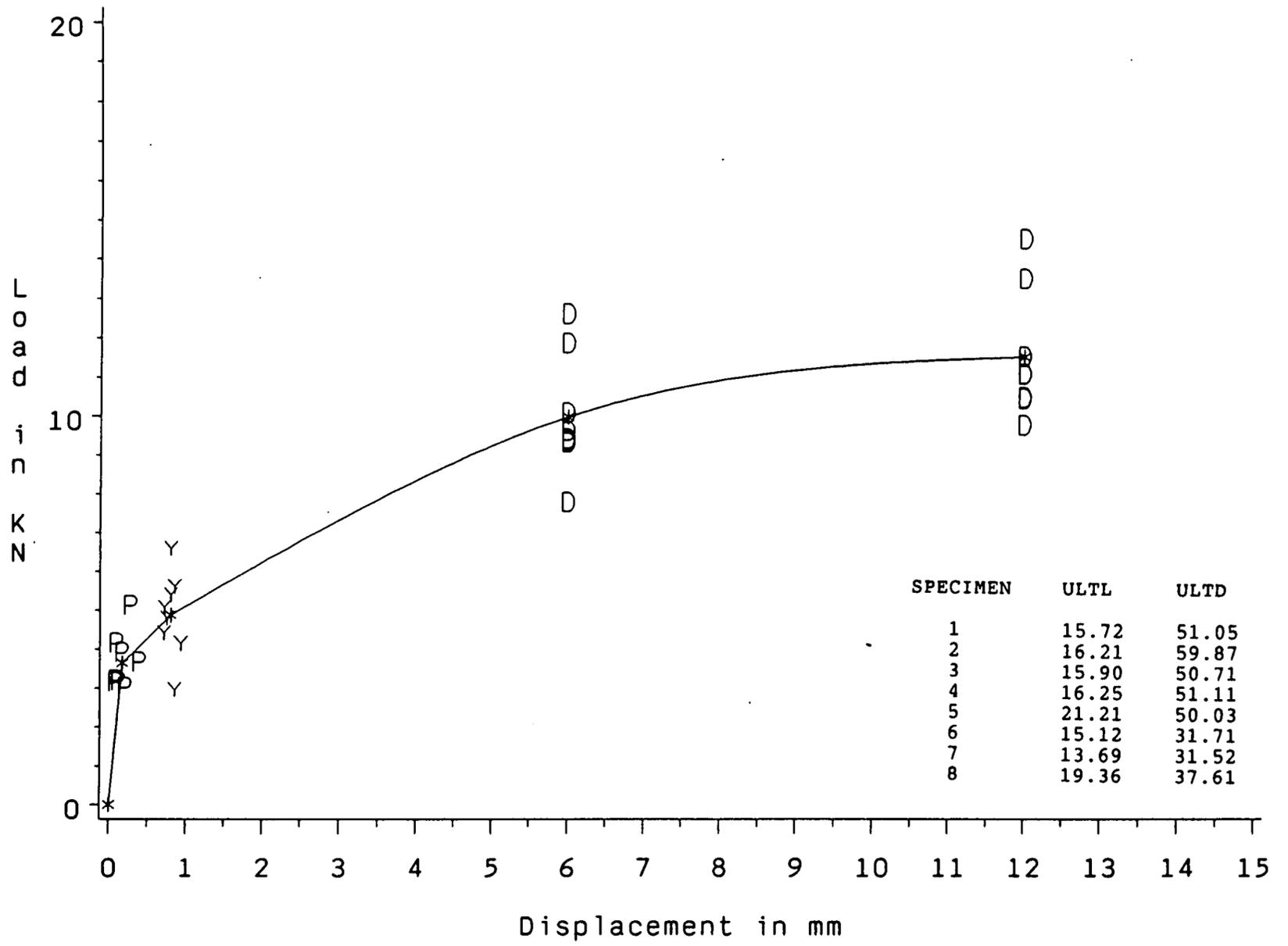
Joint code=aBC1



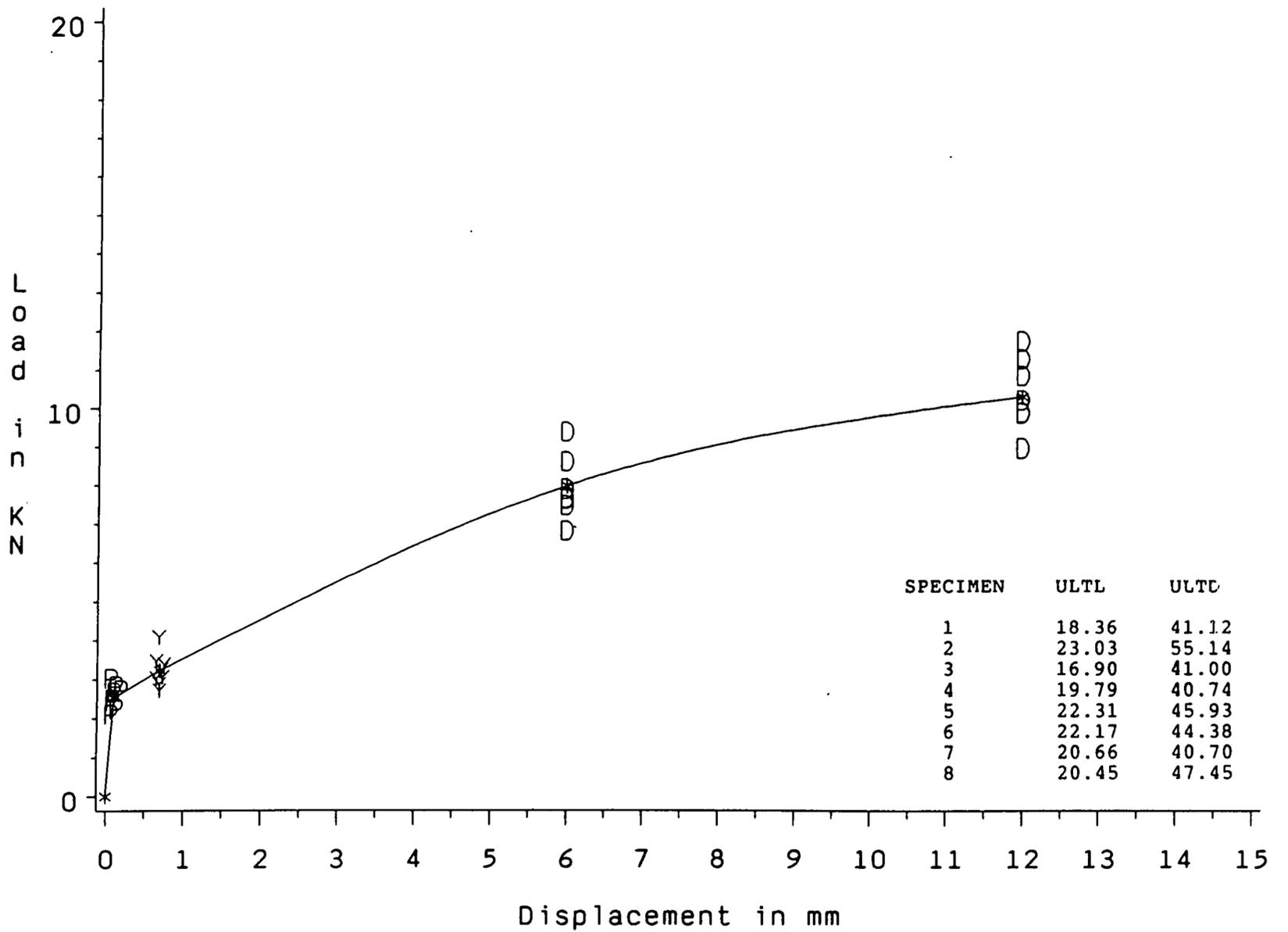
Joint code=aBE



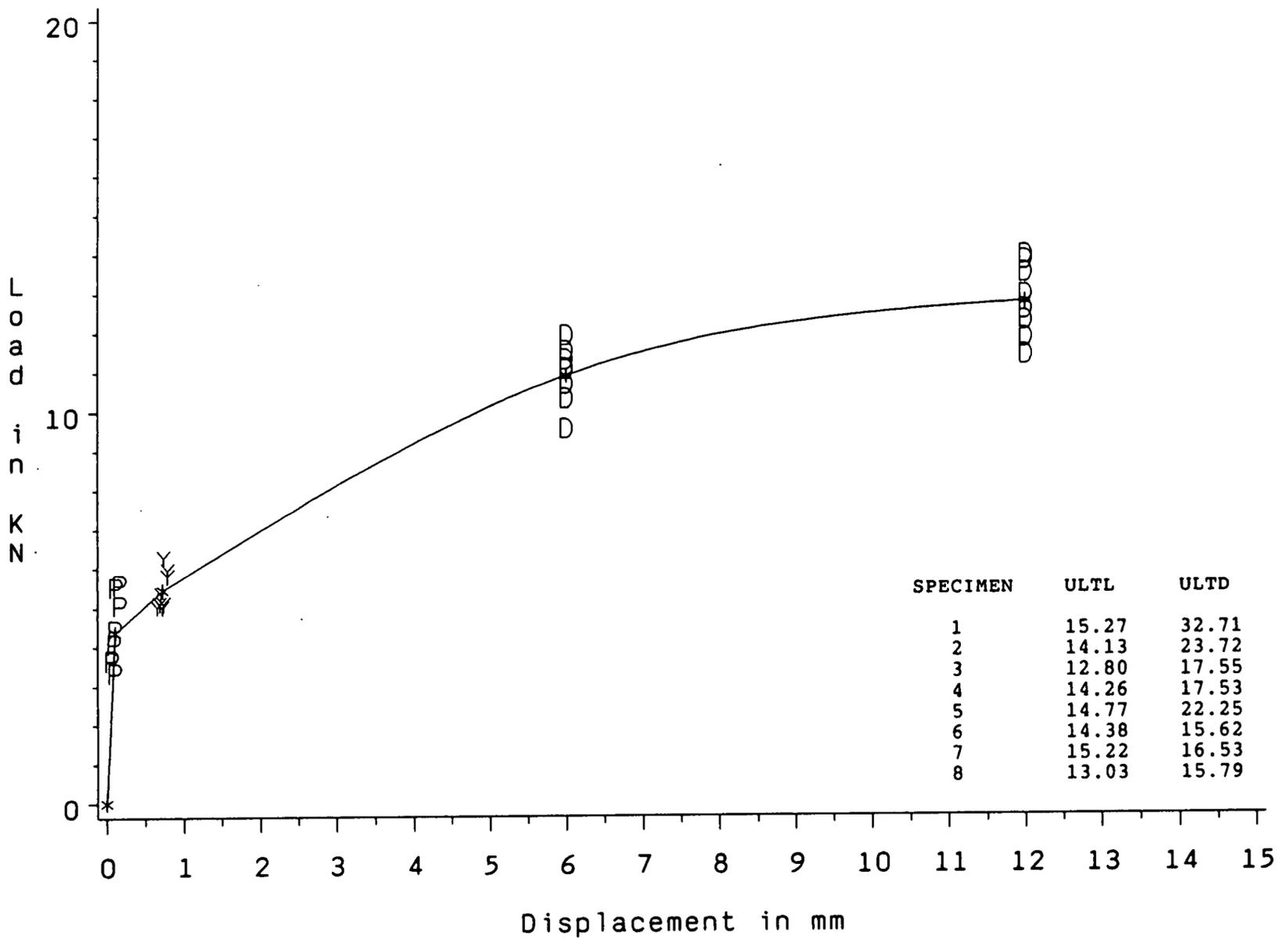
Joint code=aBE1



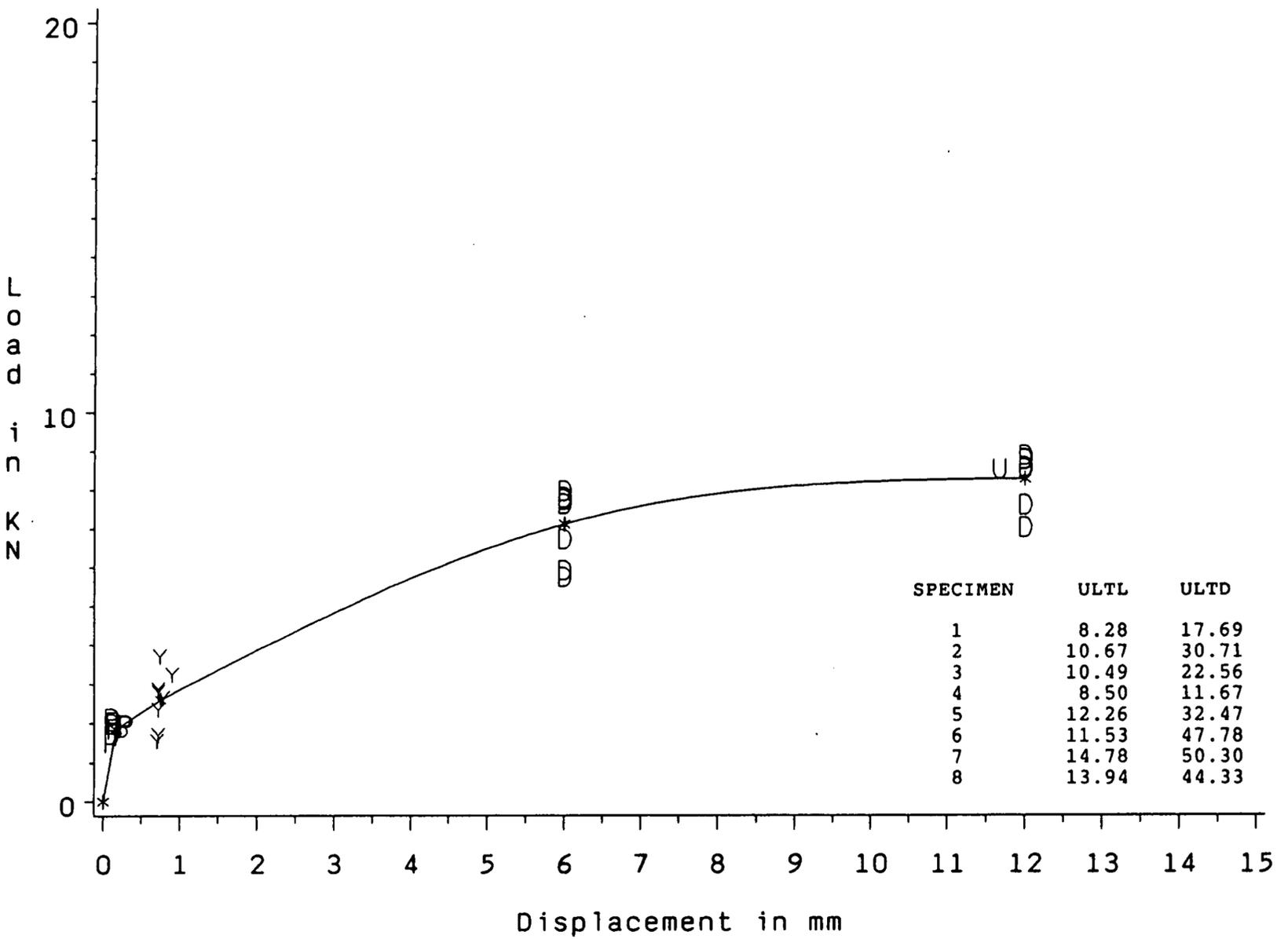
Joint code=aBAC



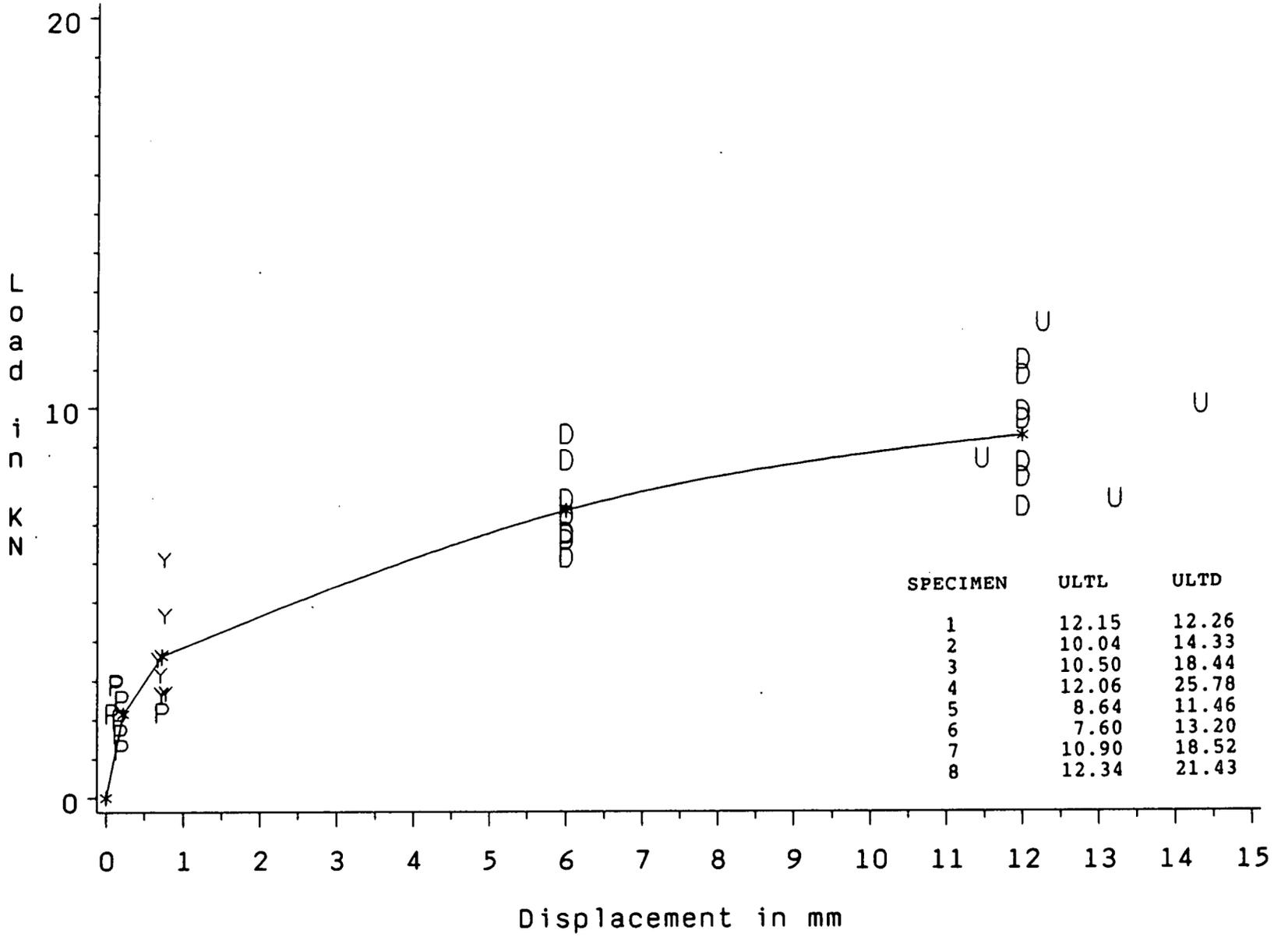
Joint code=aBAE



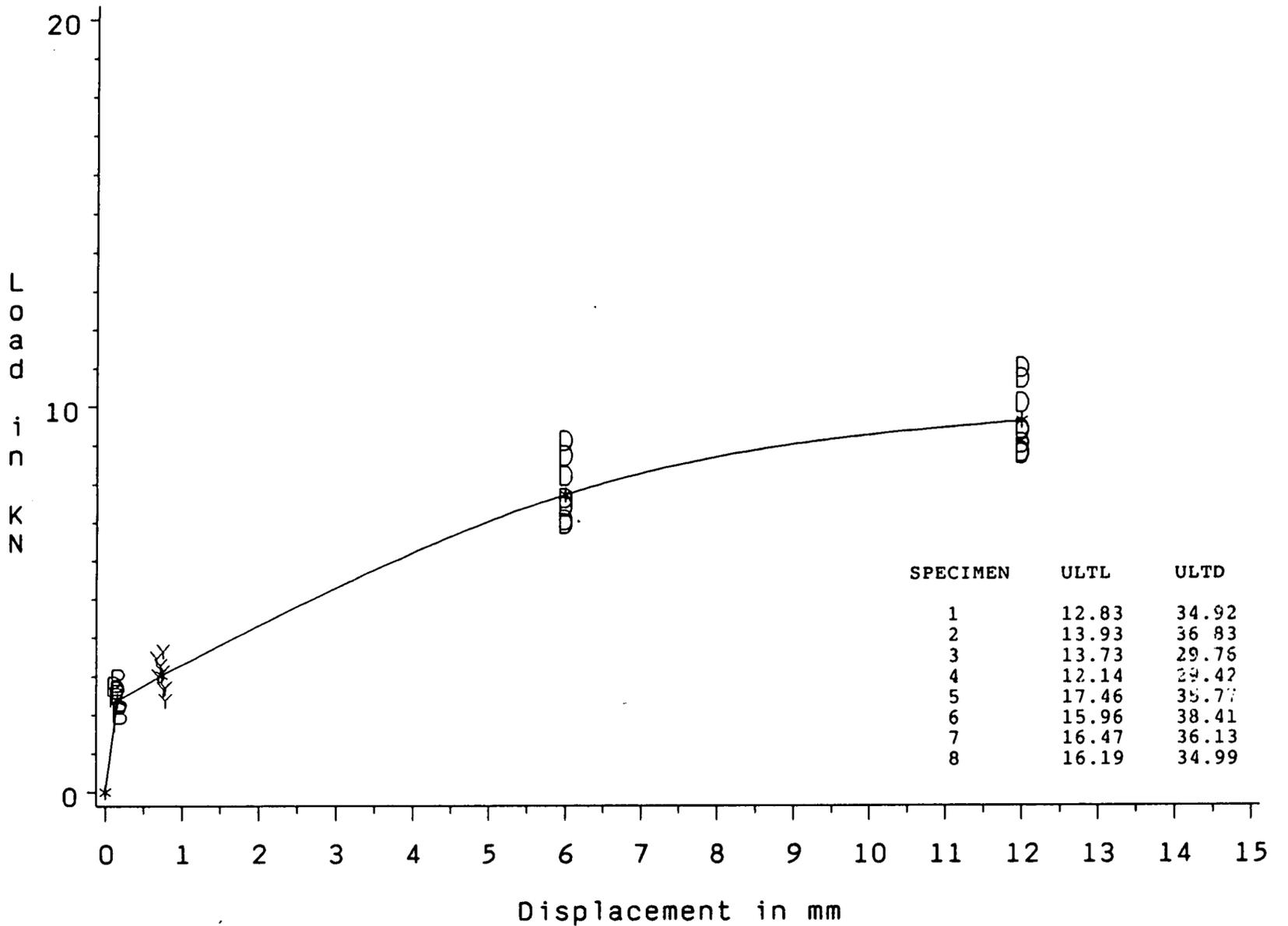
Joint code=aBCE



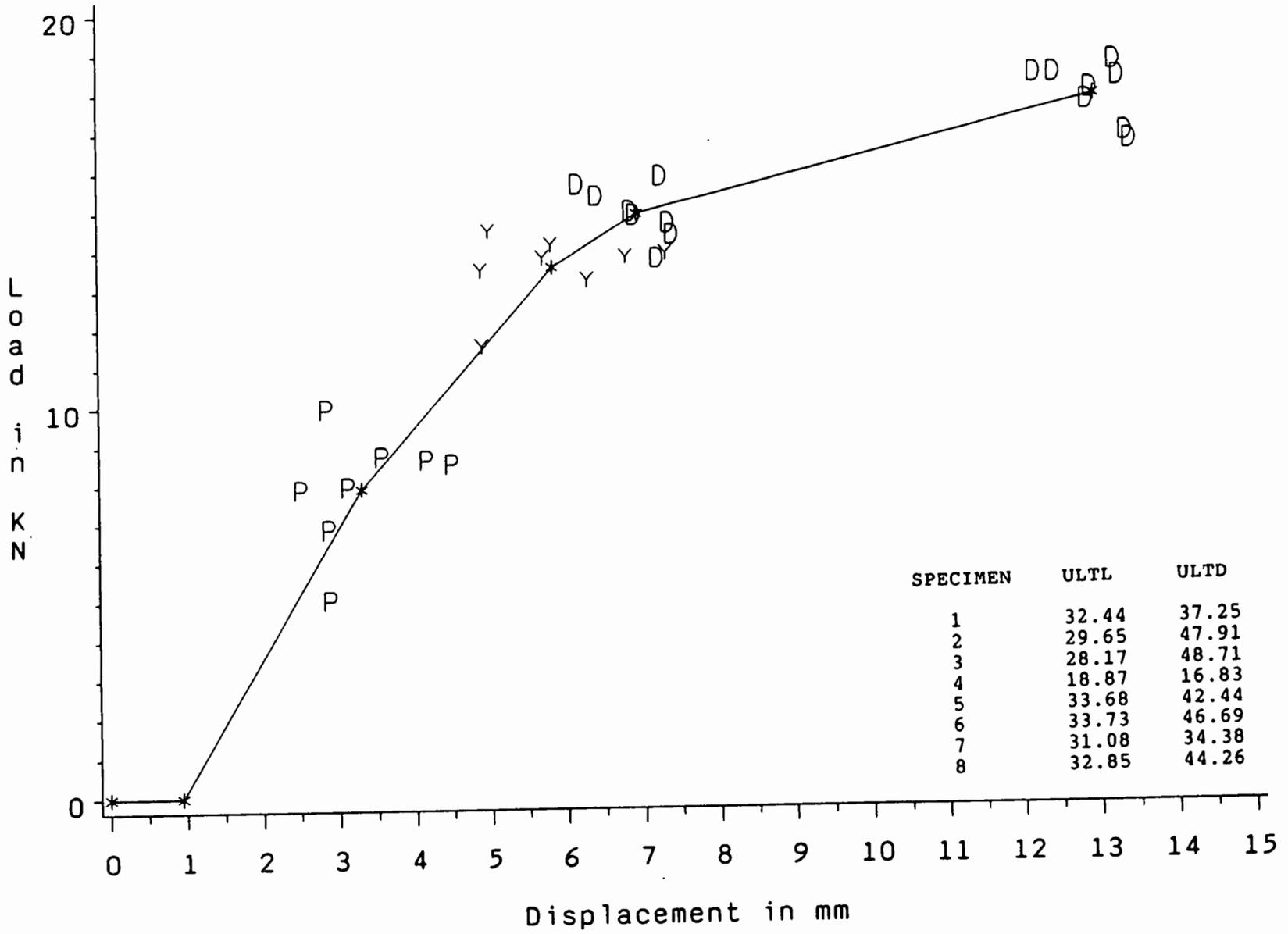
Joint code=aBACE



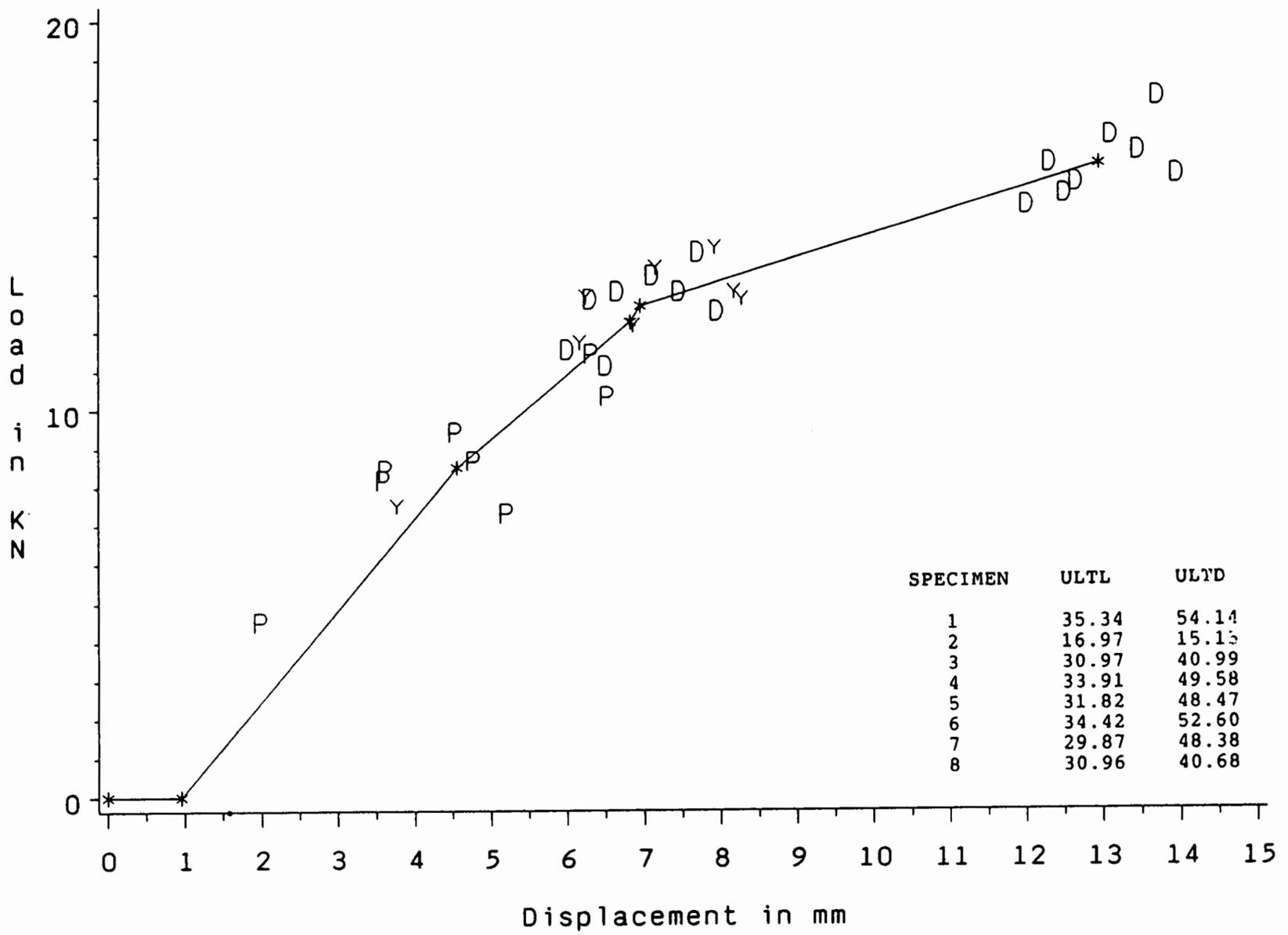
Joint code=aBAC1



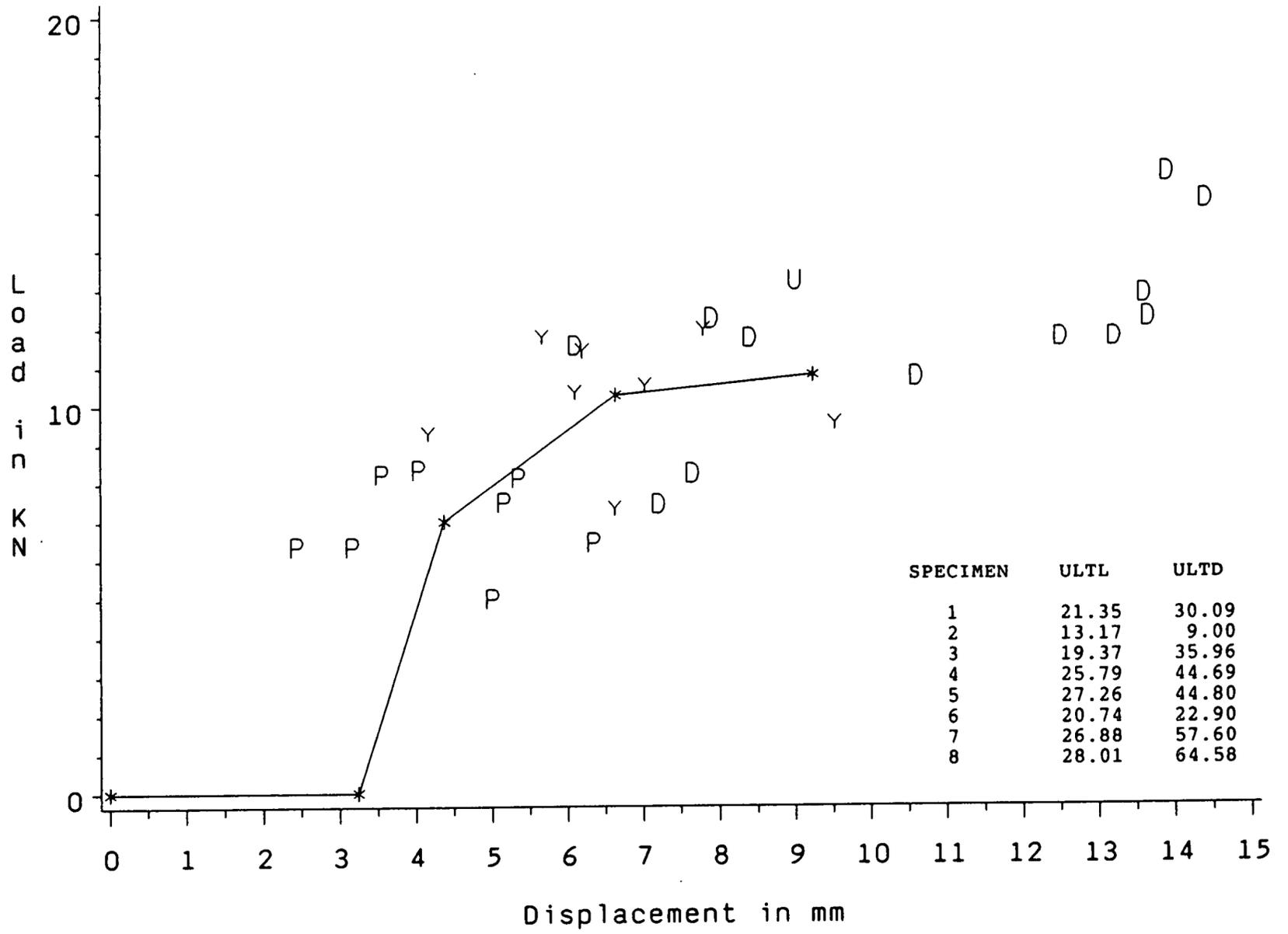
Joint code=bA



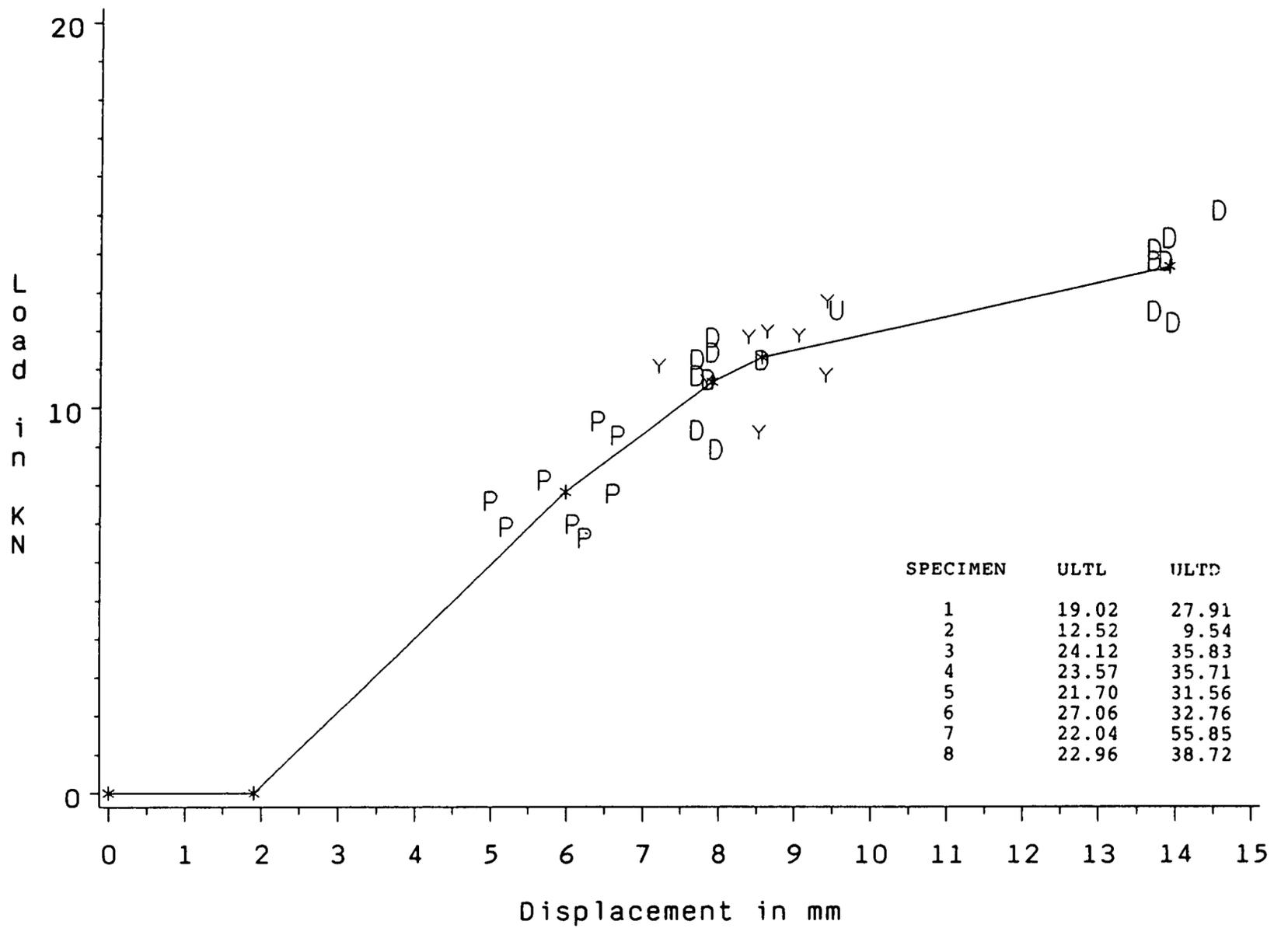
Joint code=bAB



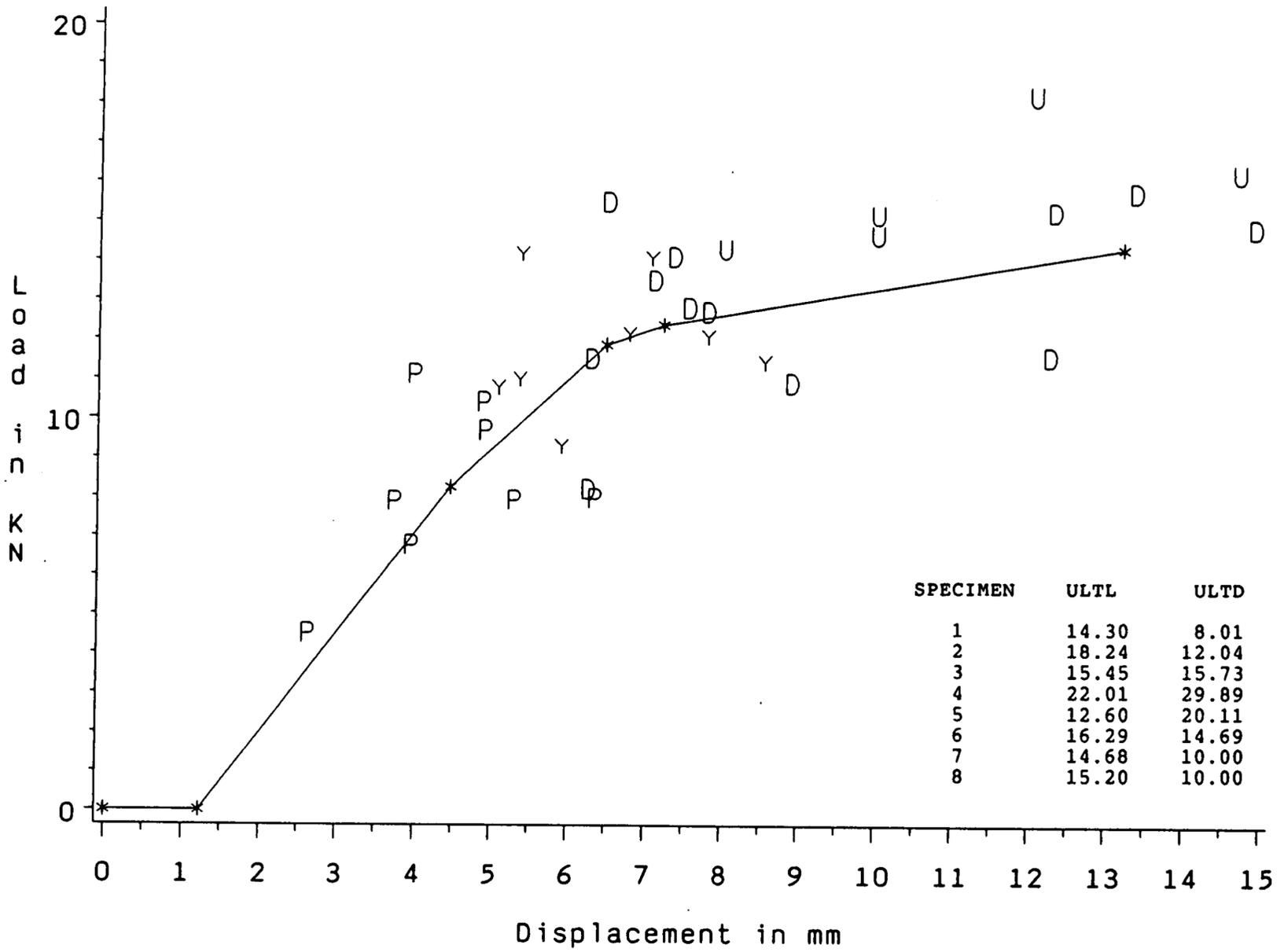
Joint code=bABC



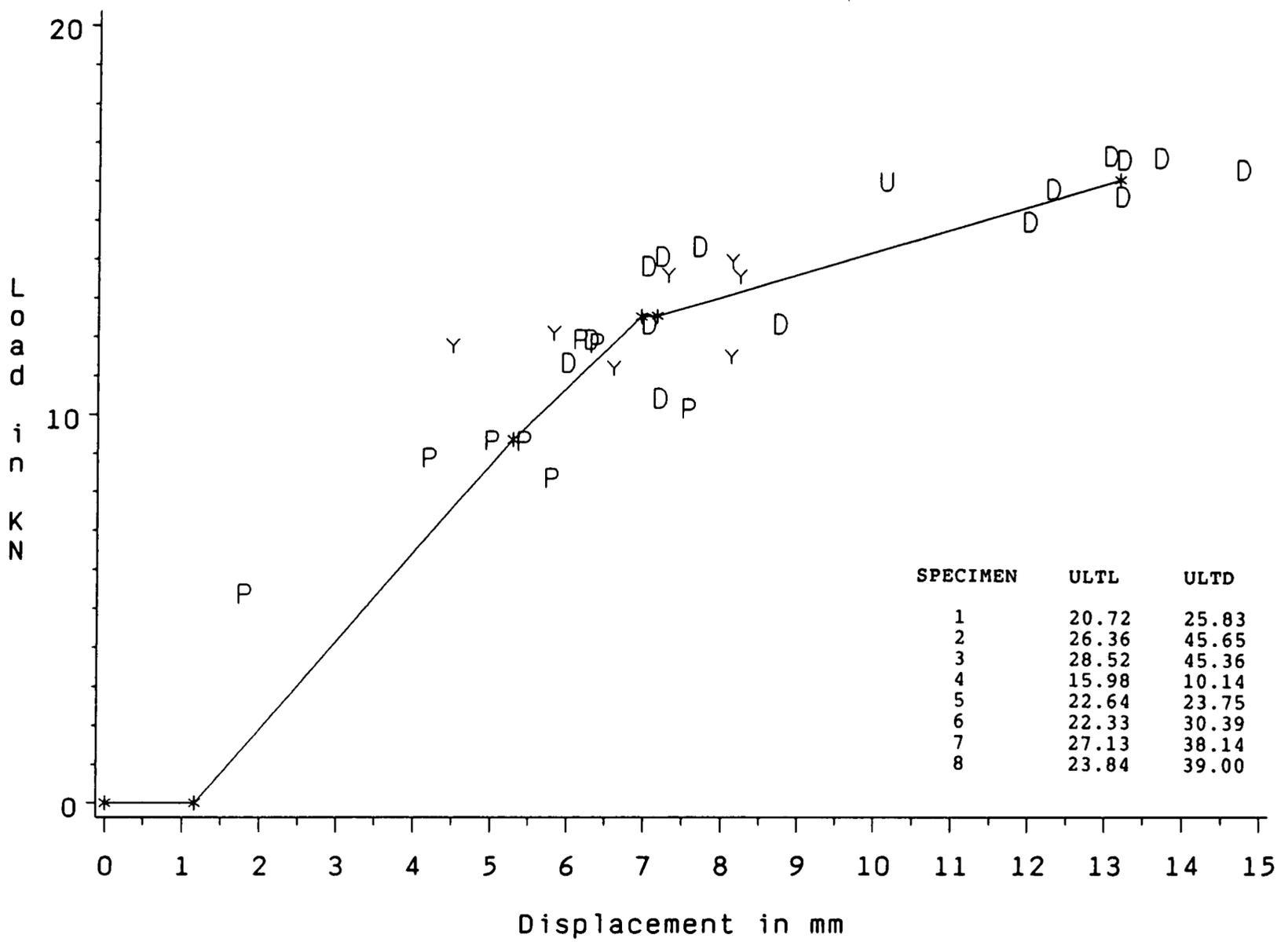
Joint code=bABC1



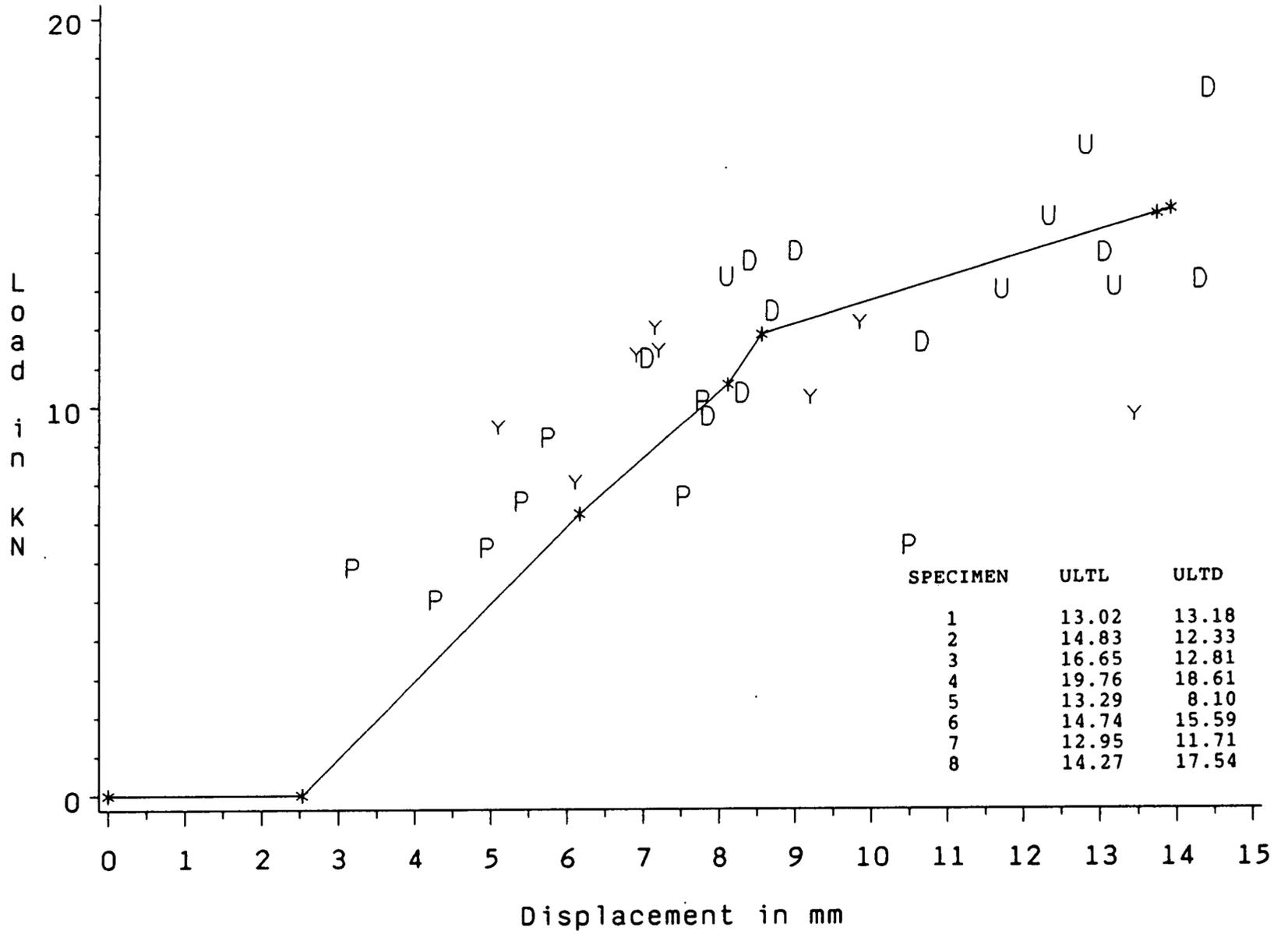
Joint code=bABE



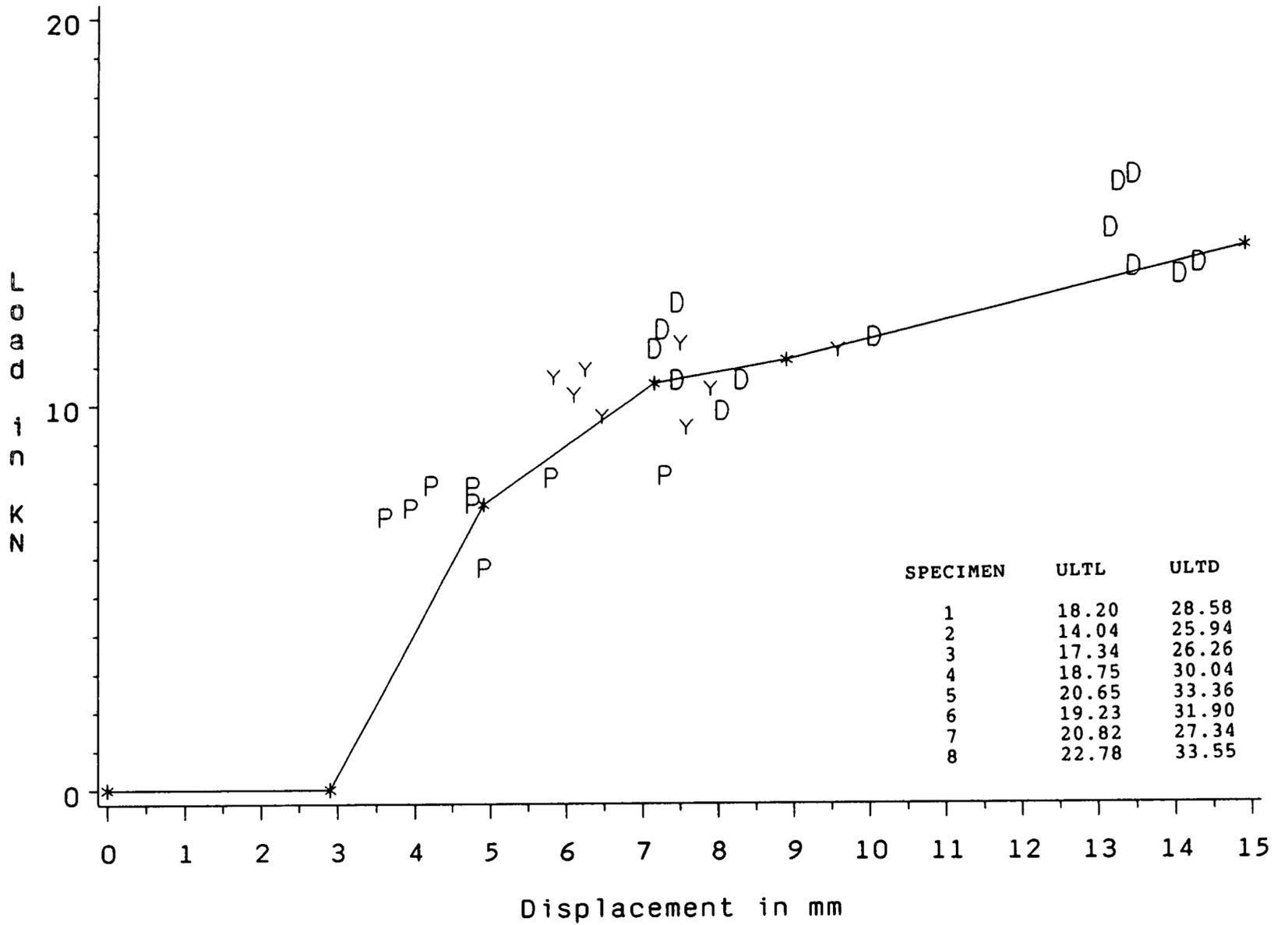
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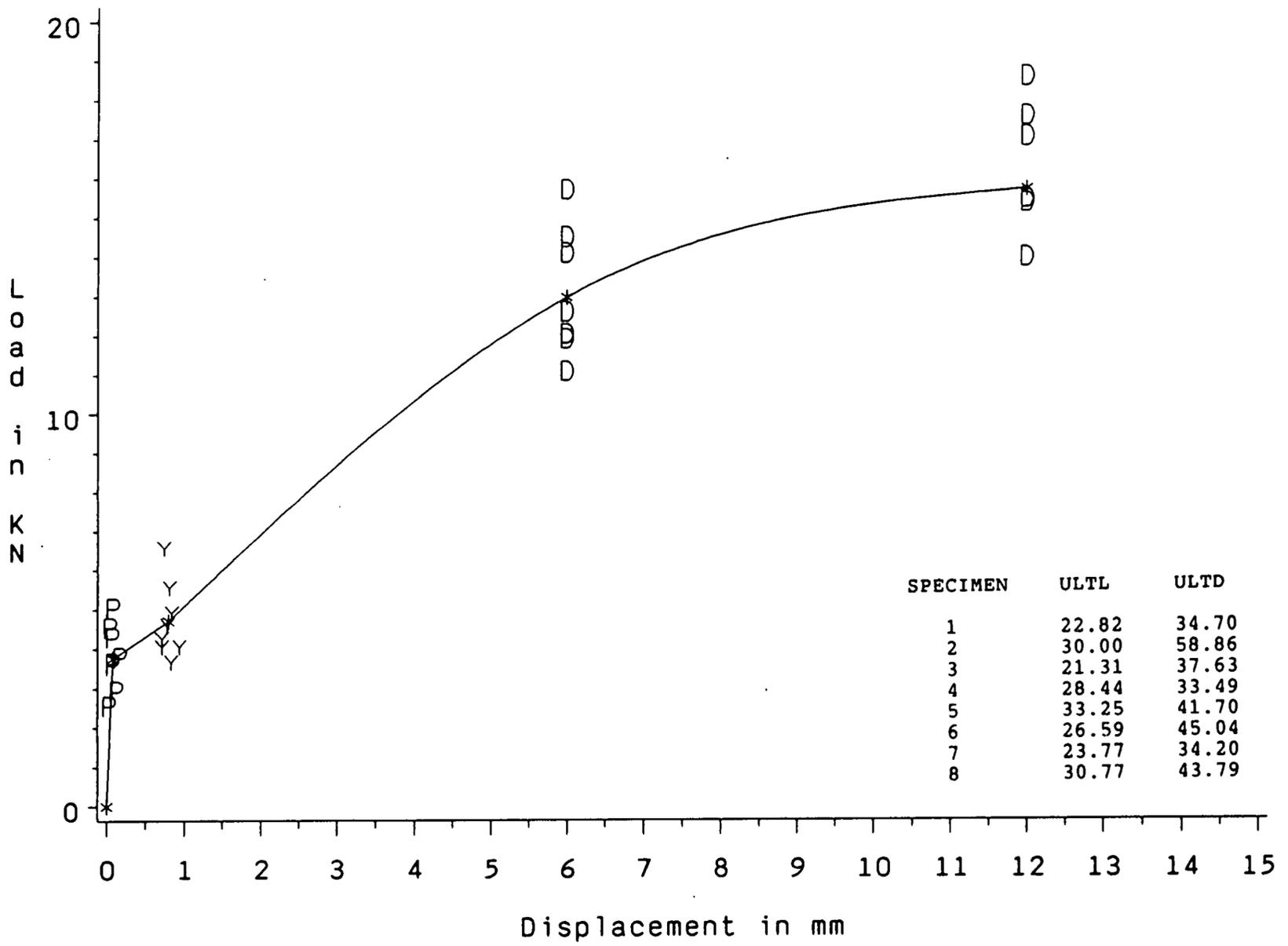
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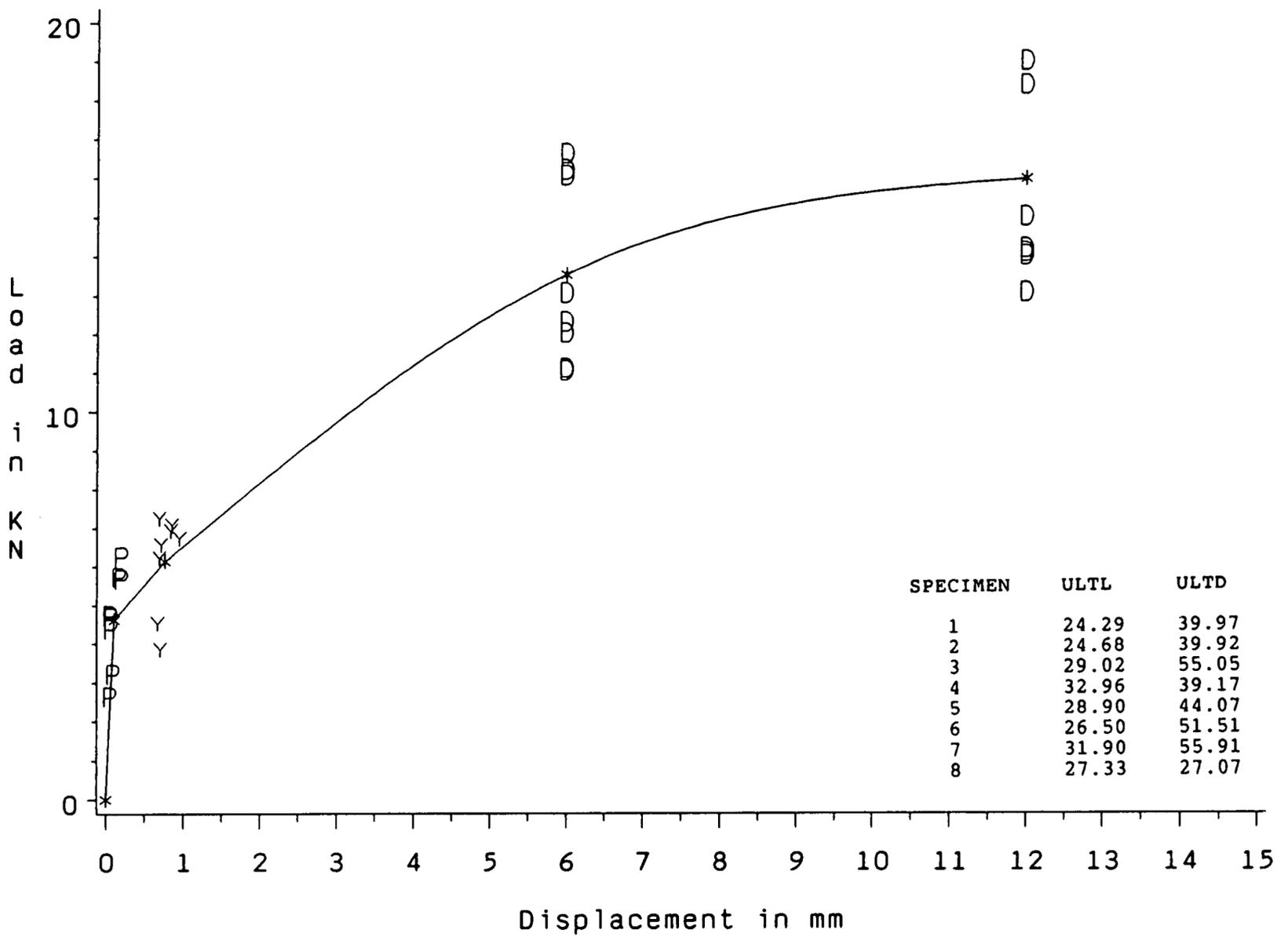
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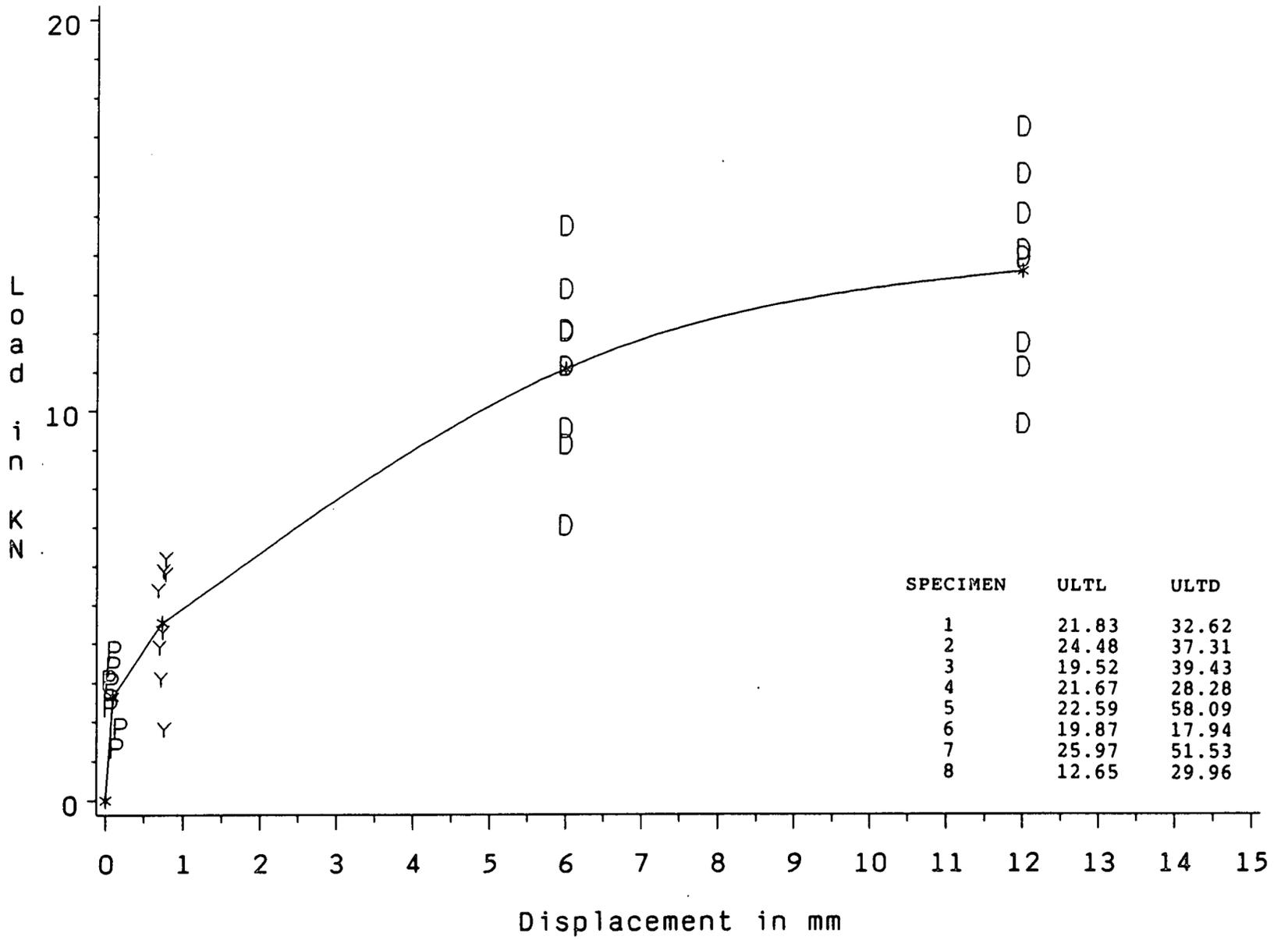
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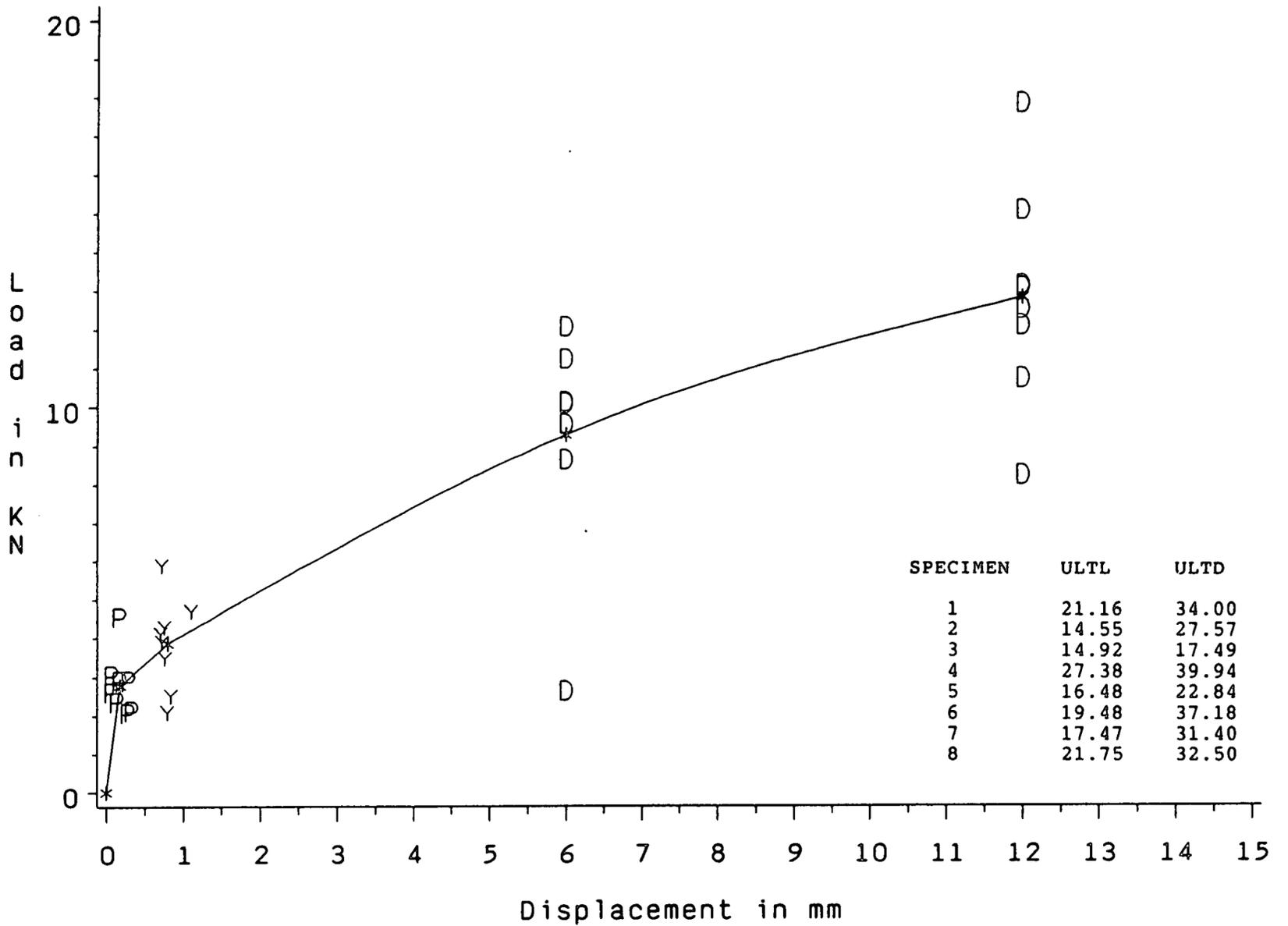
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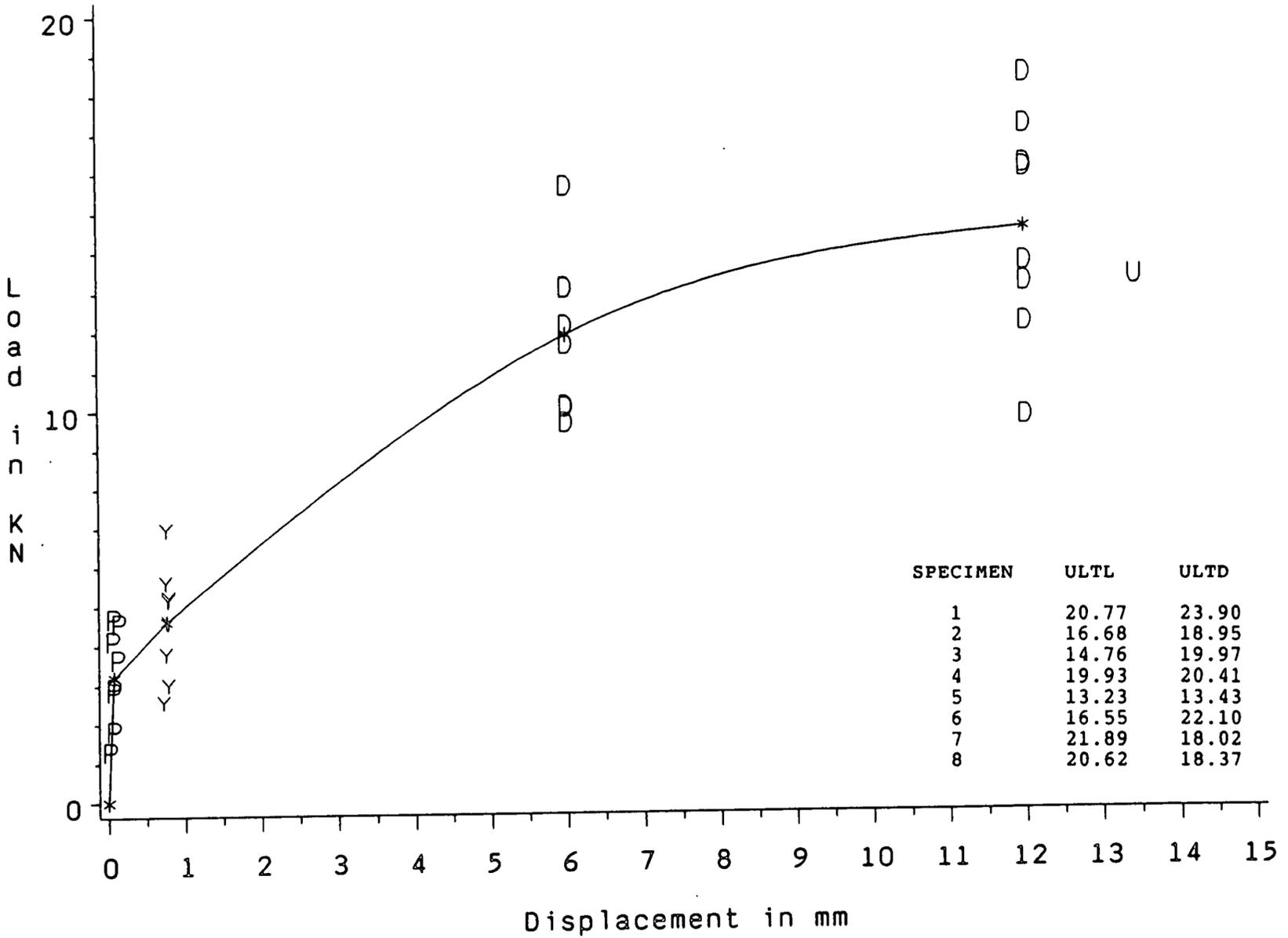
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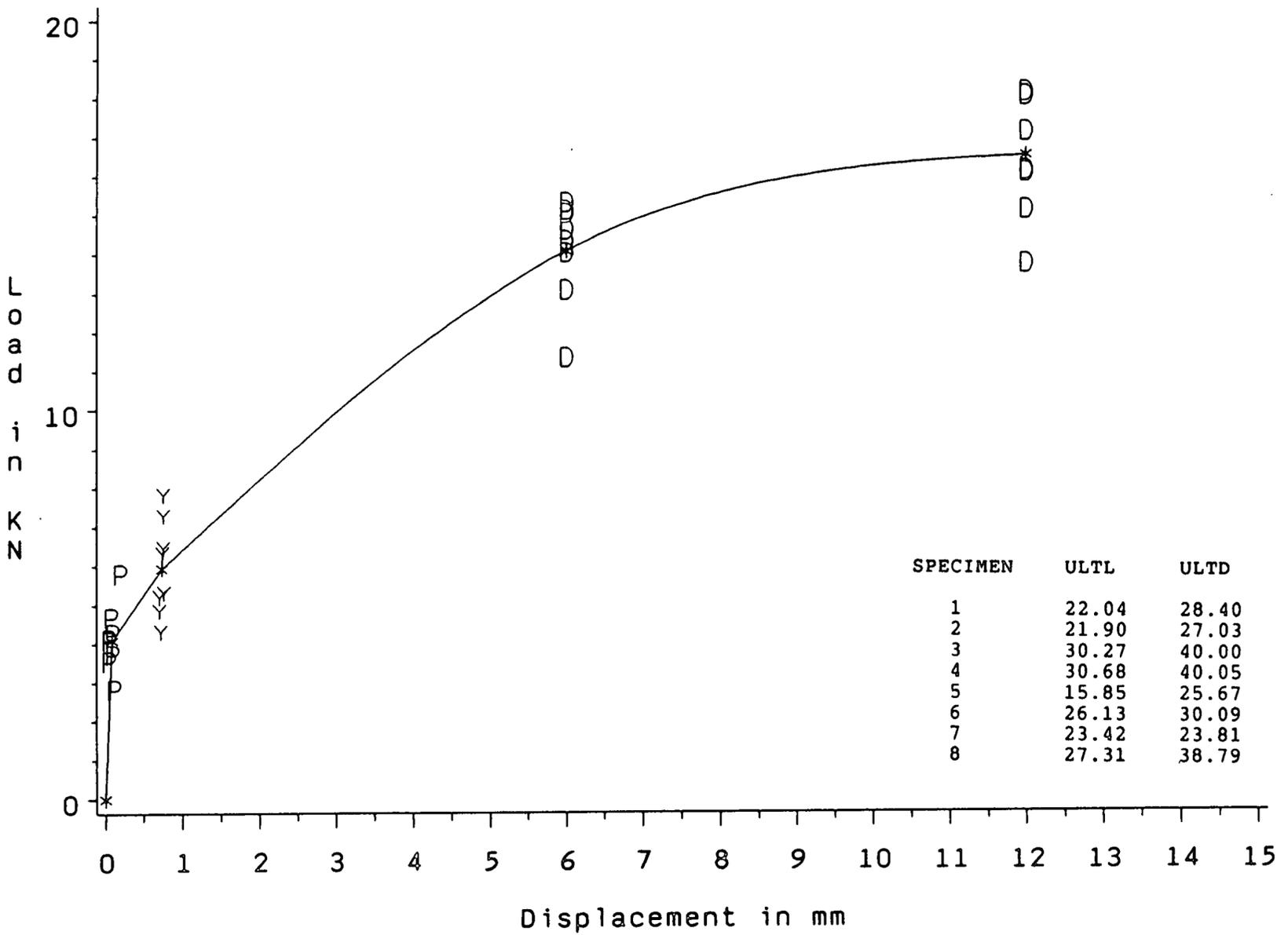
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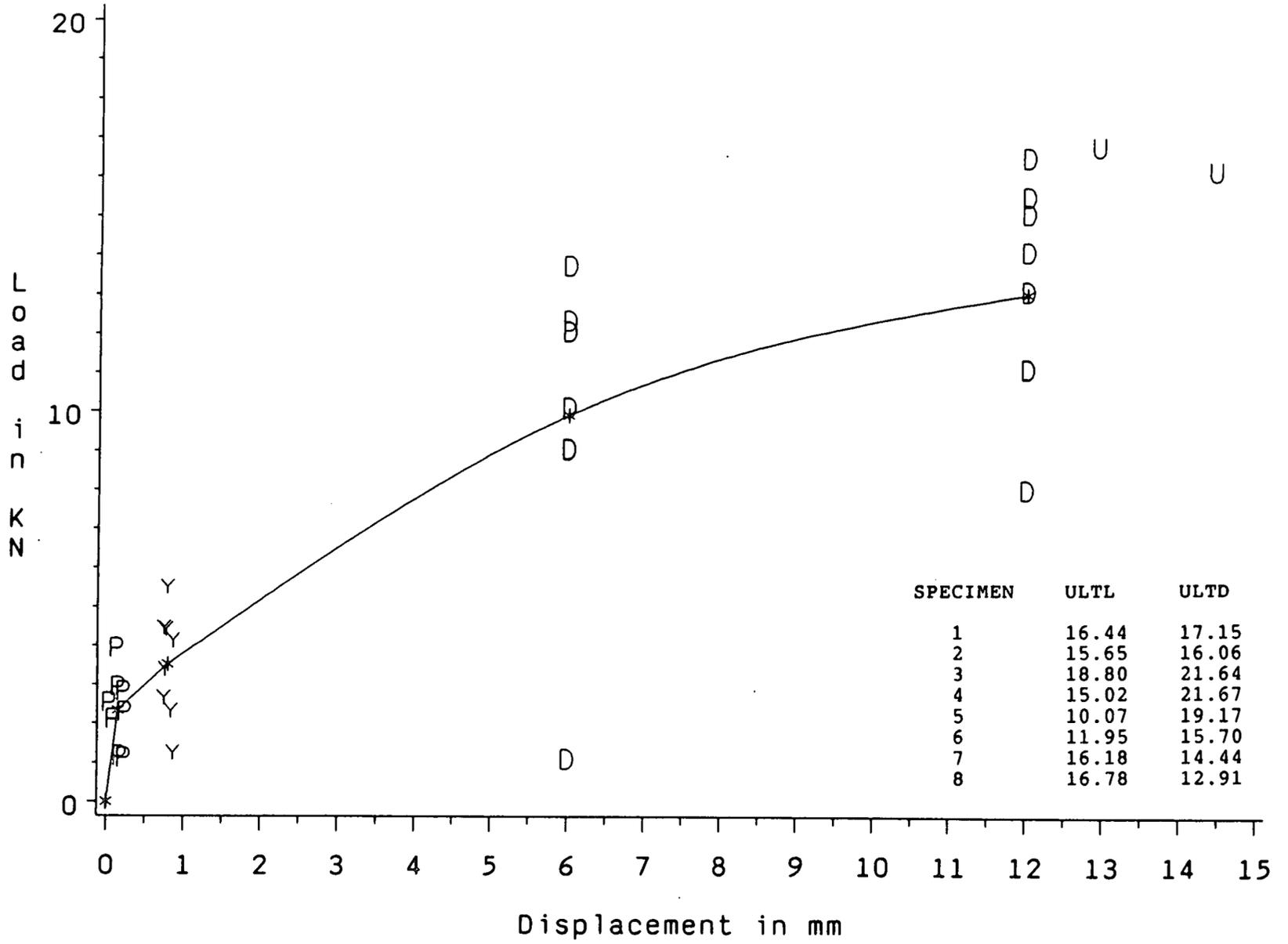
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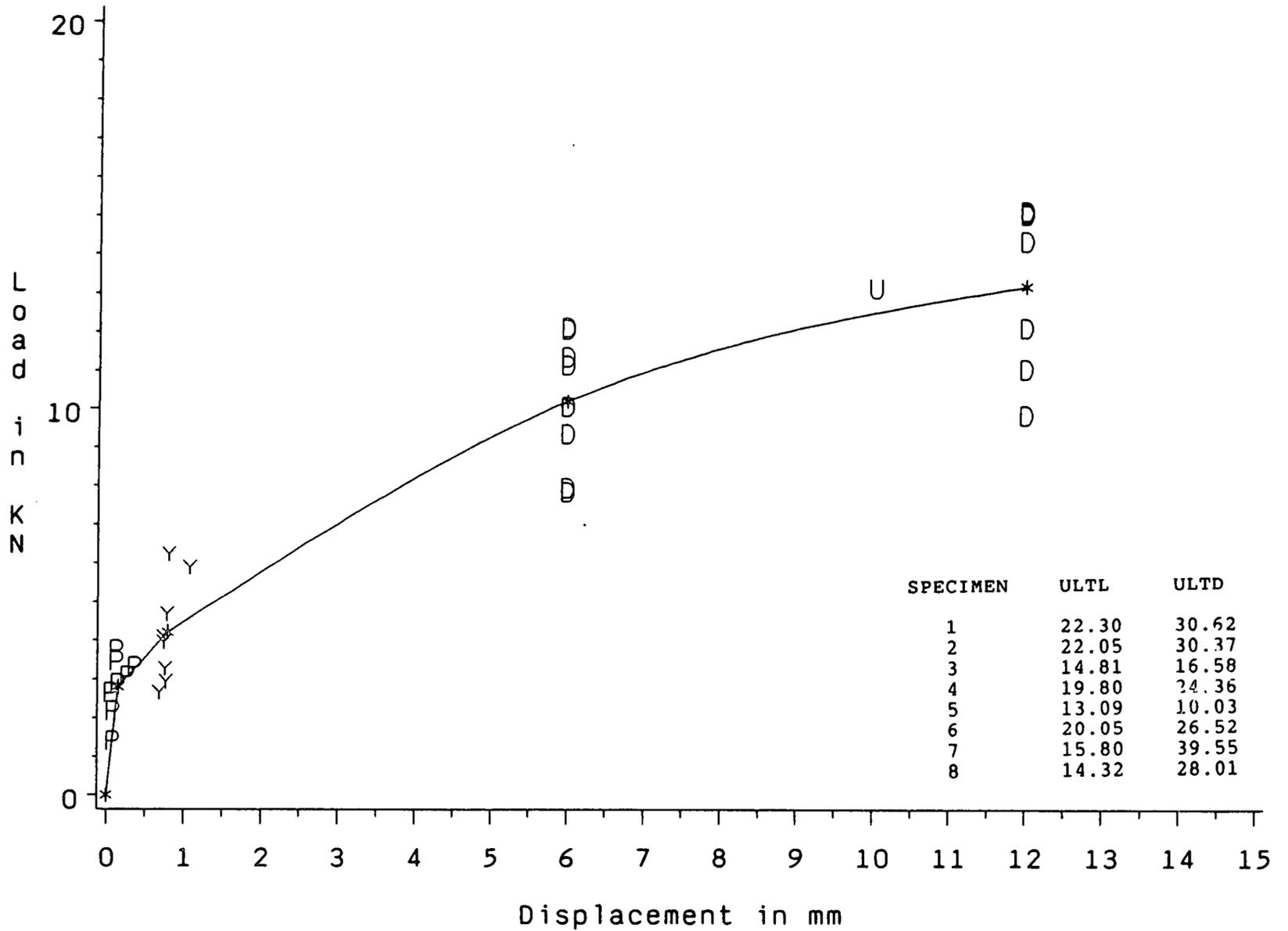
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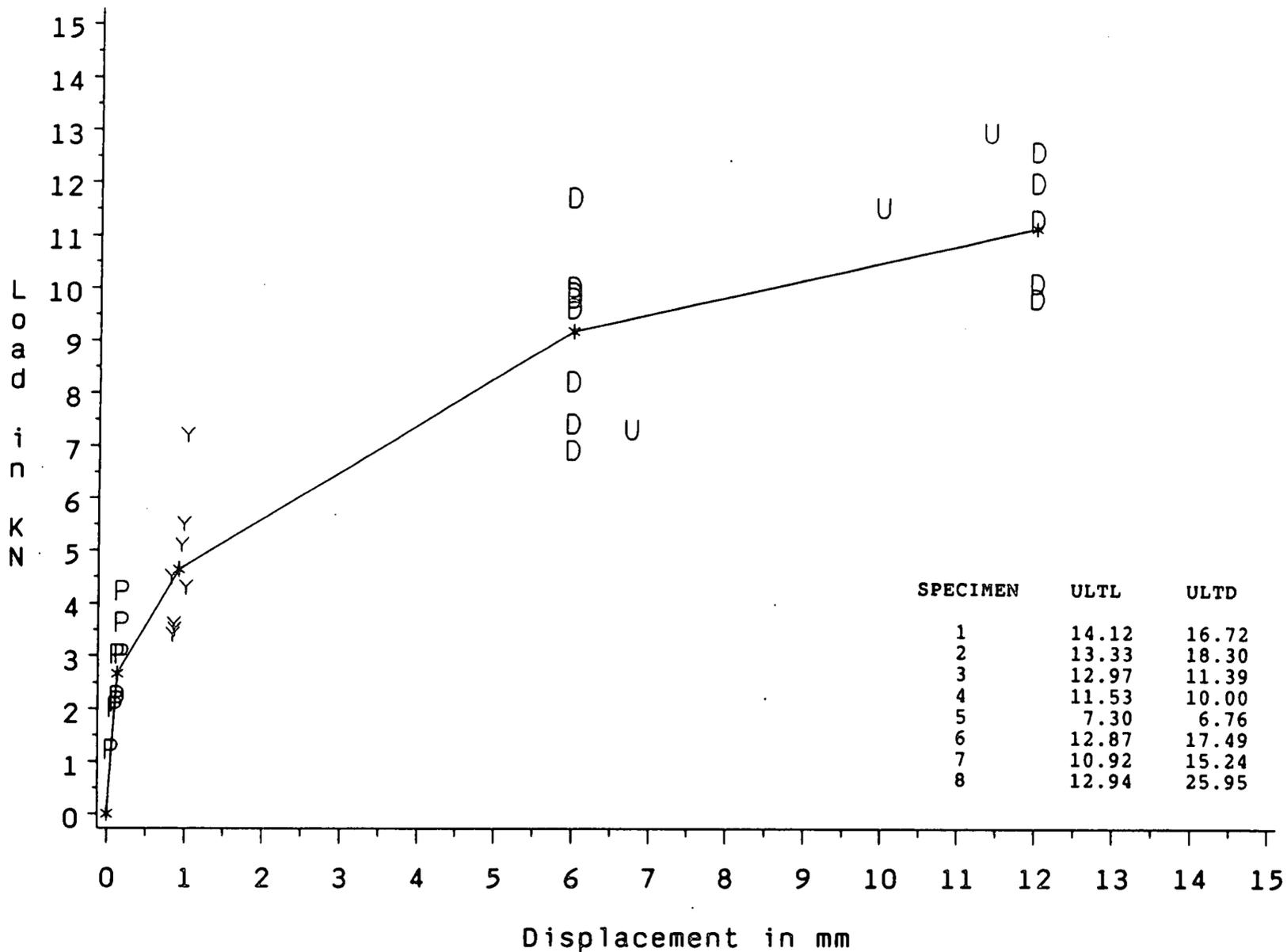
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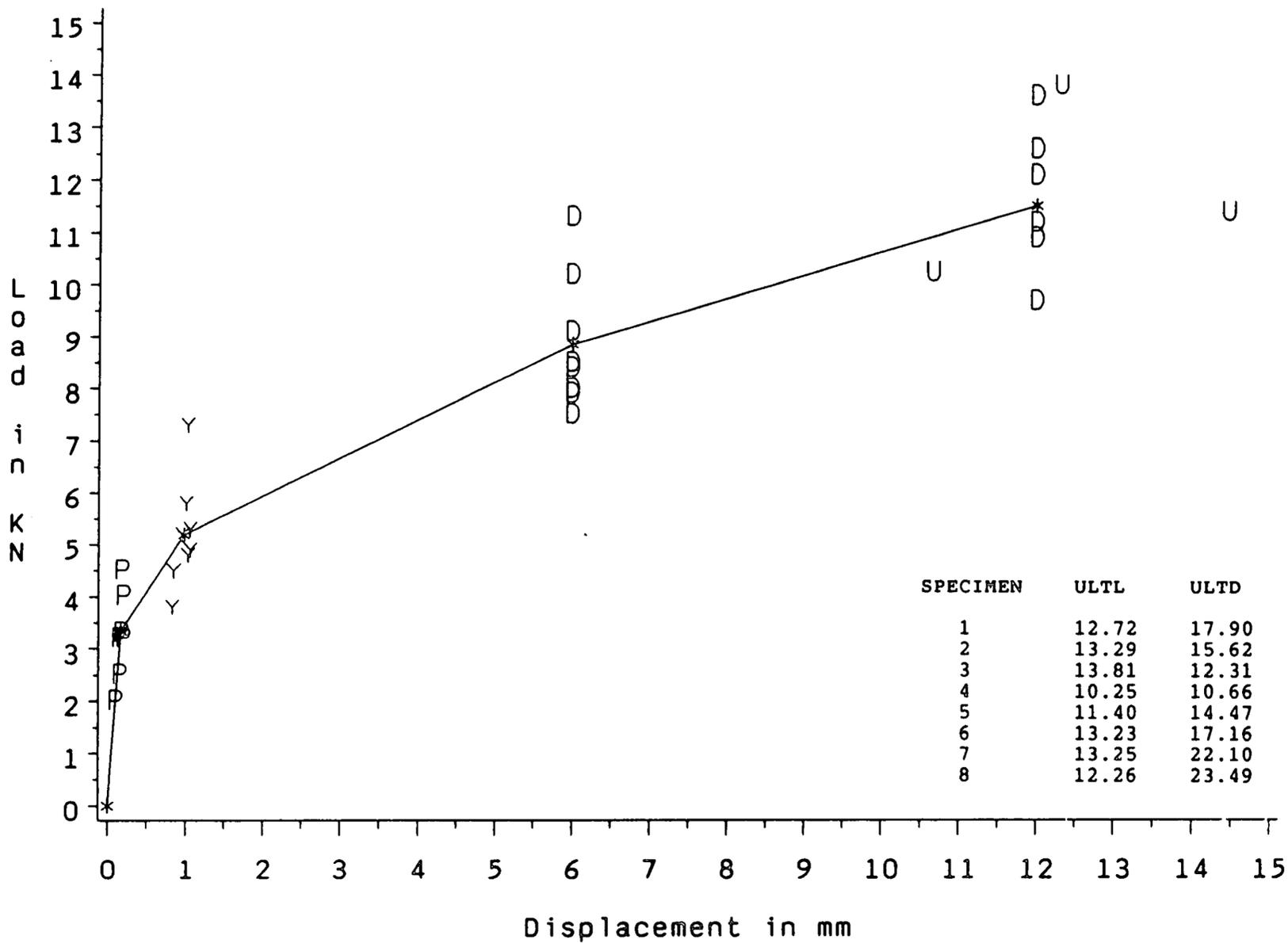
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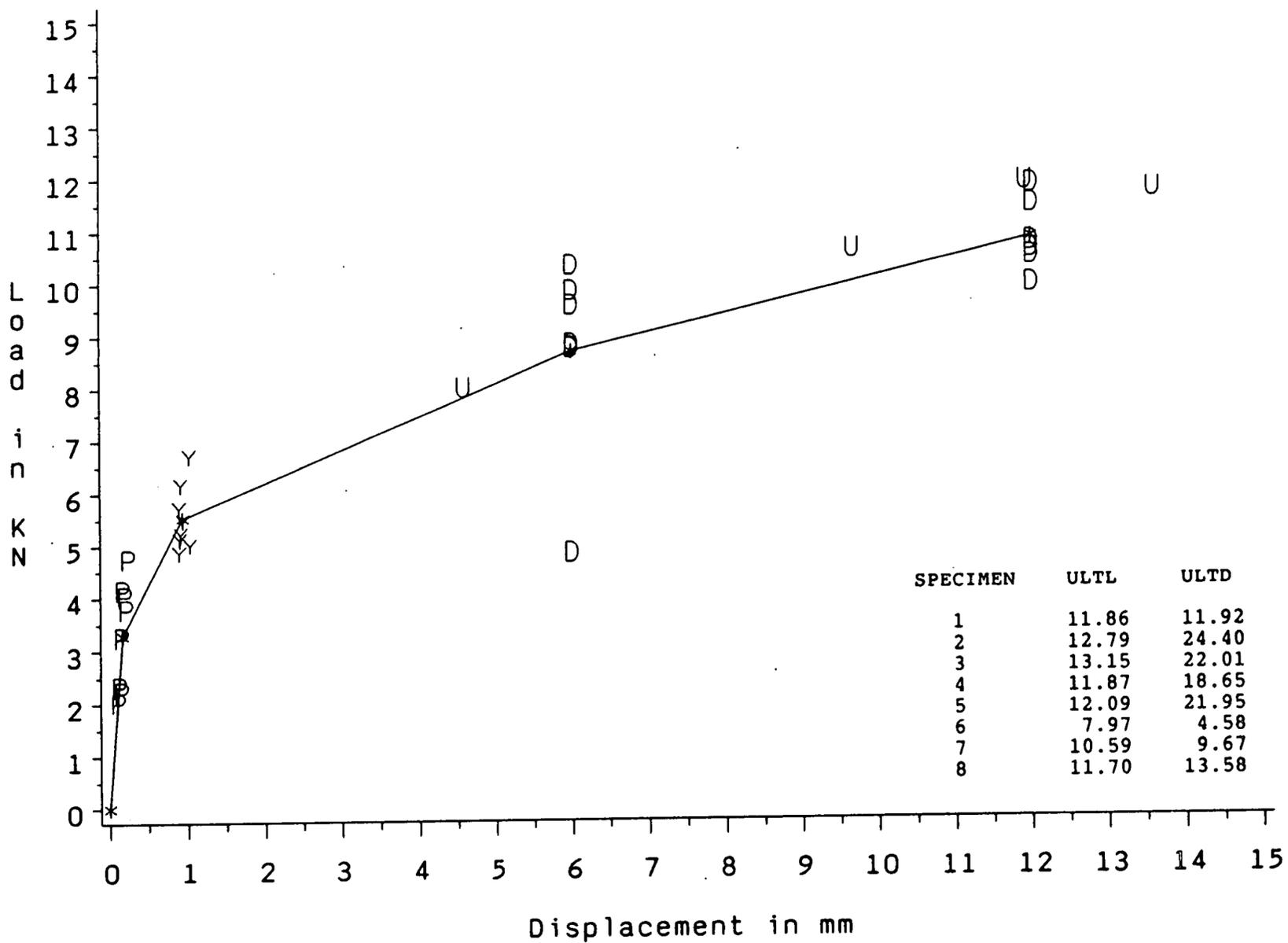
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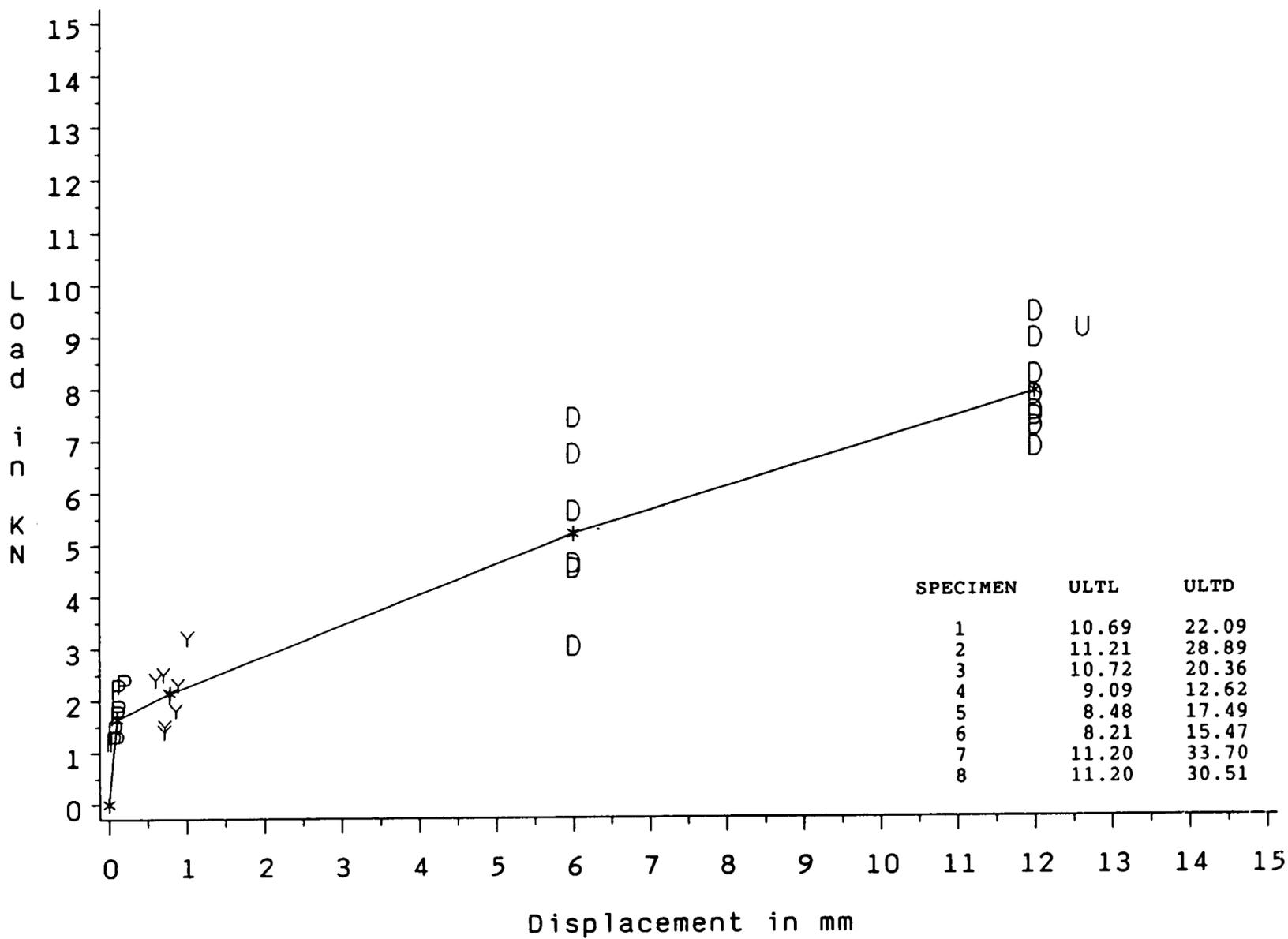
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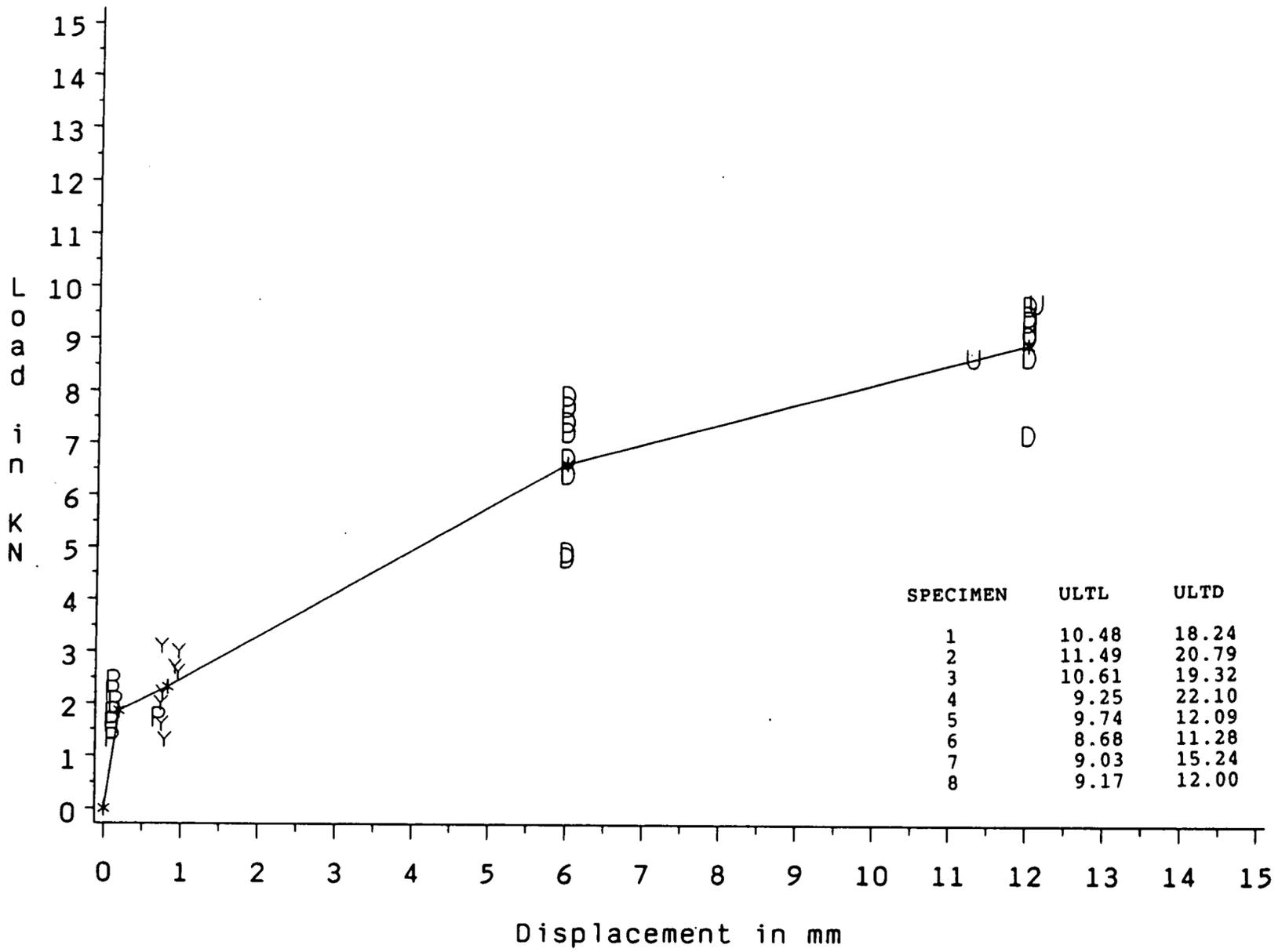
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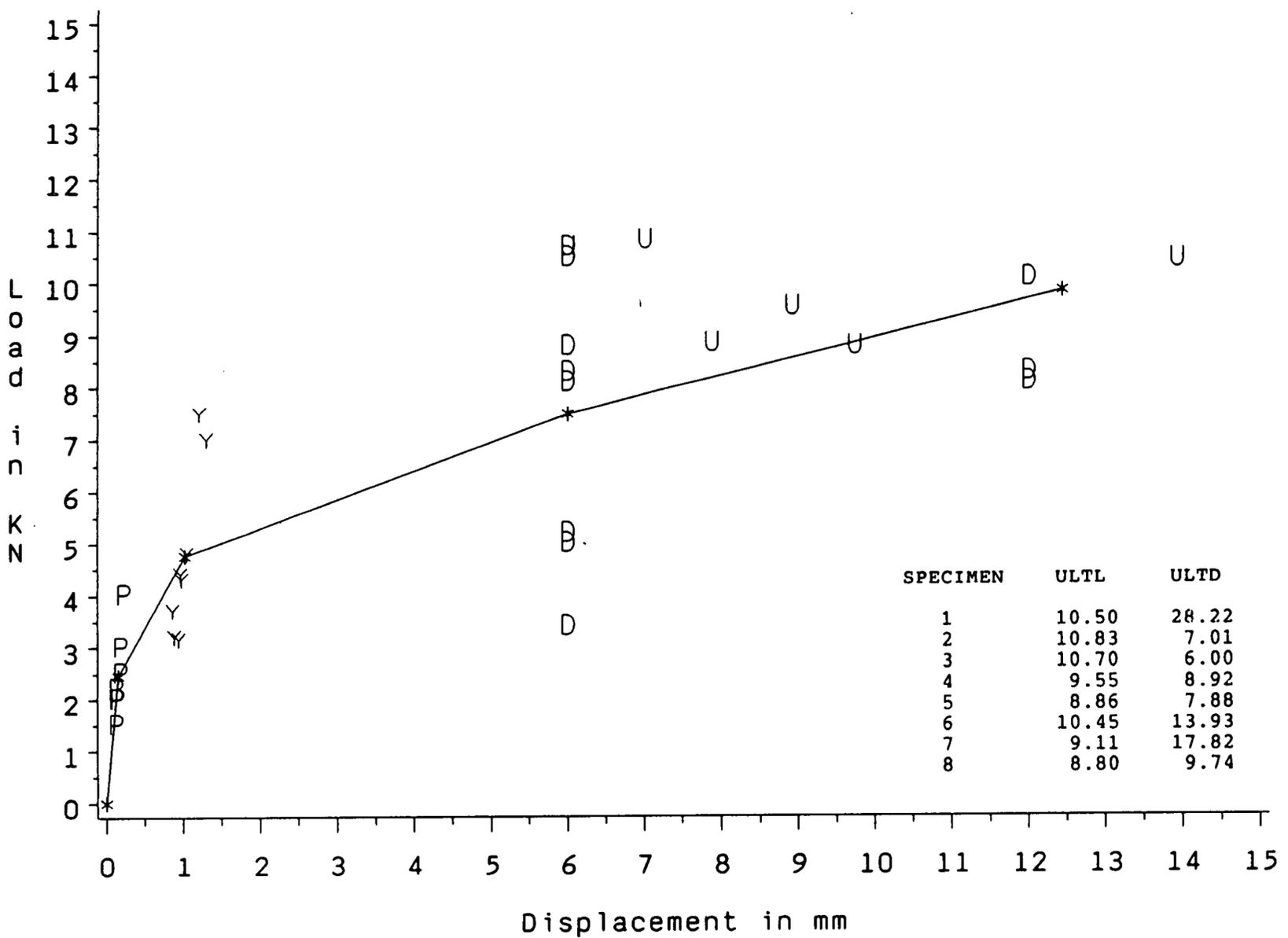
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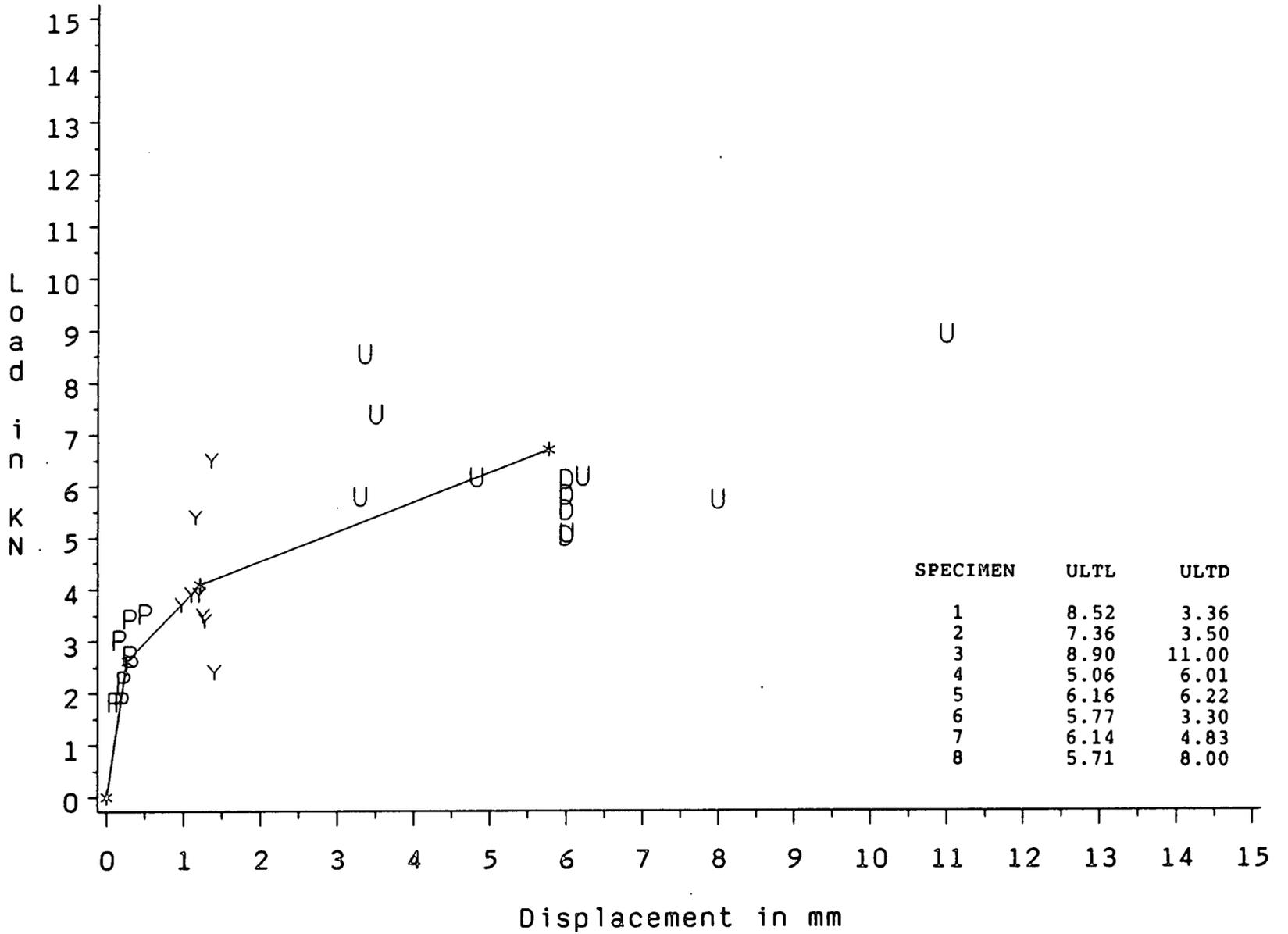
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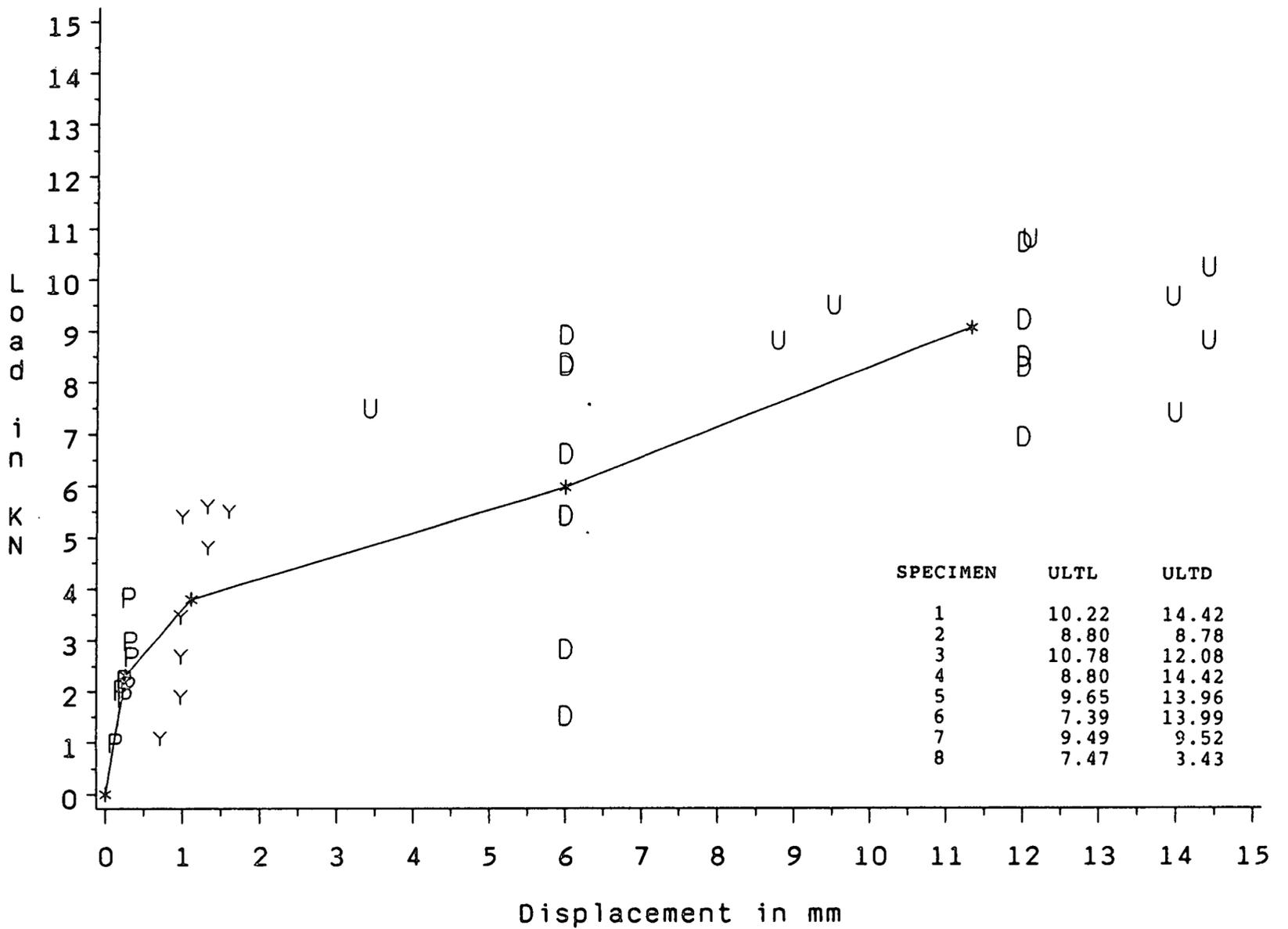
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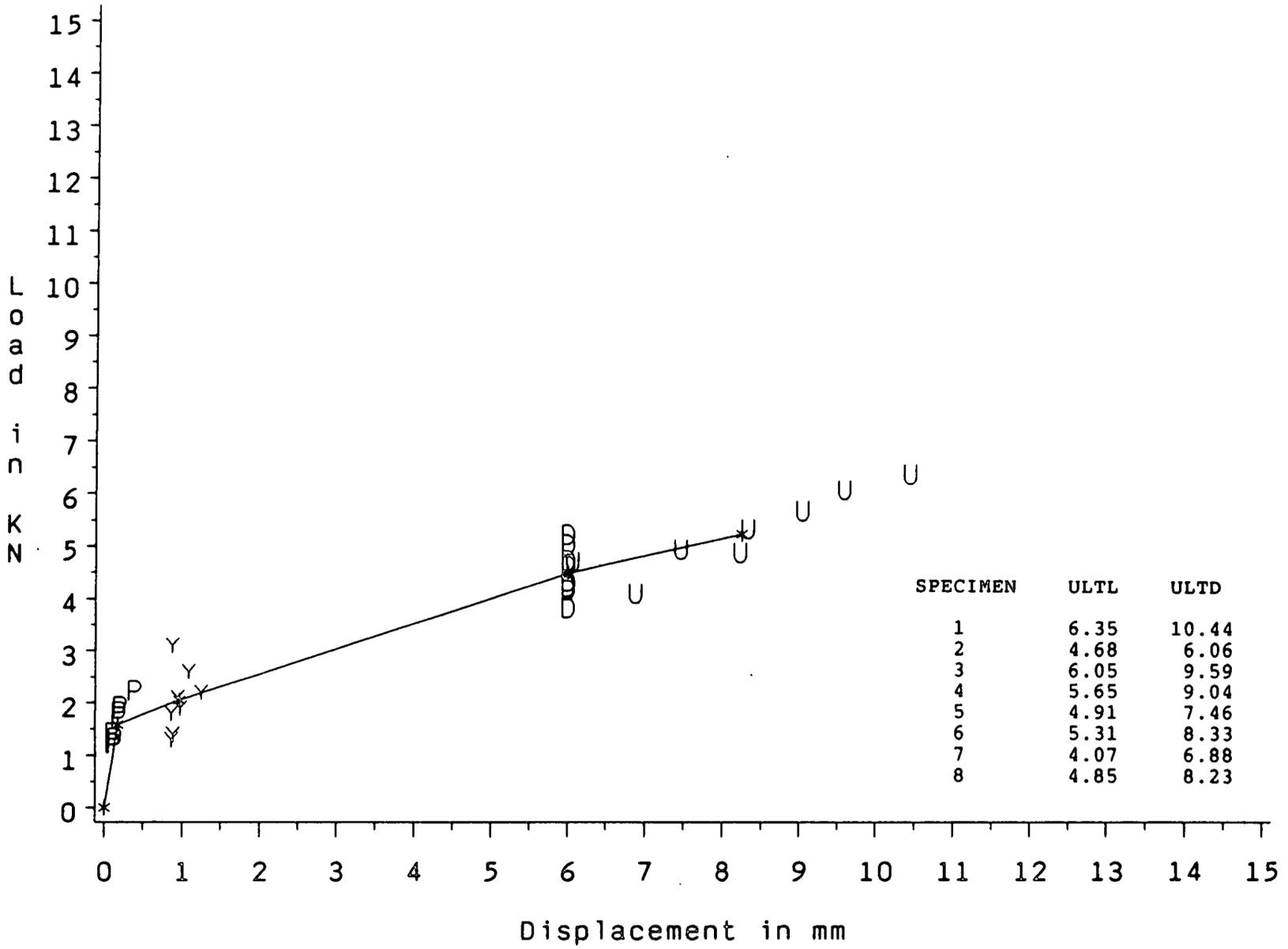
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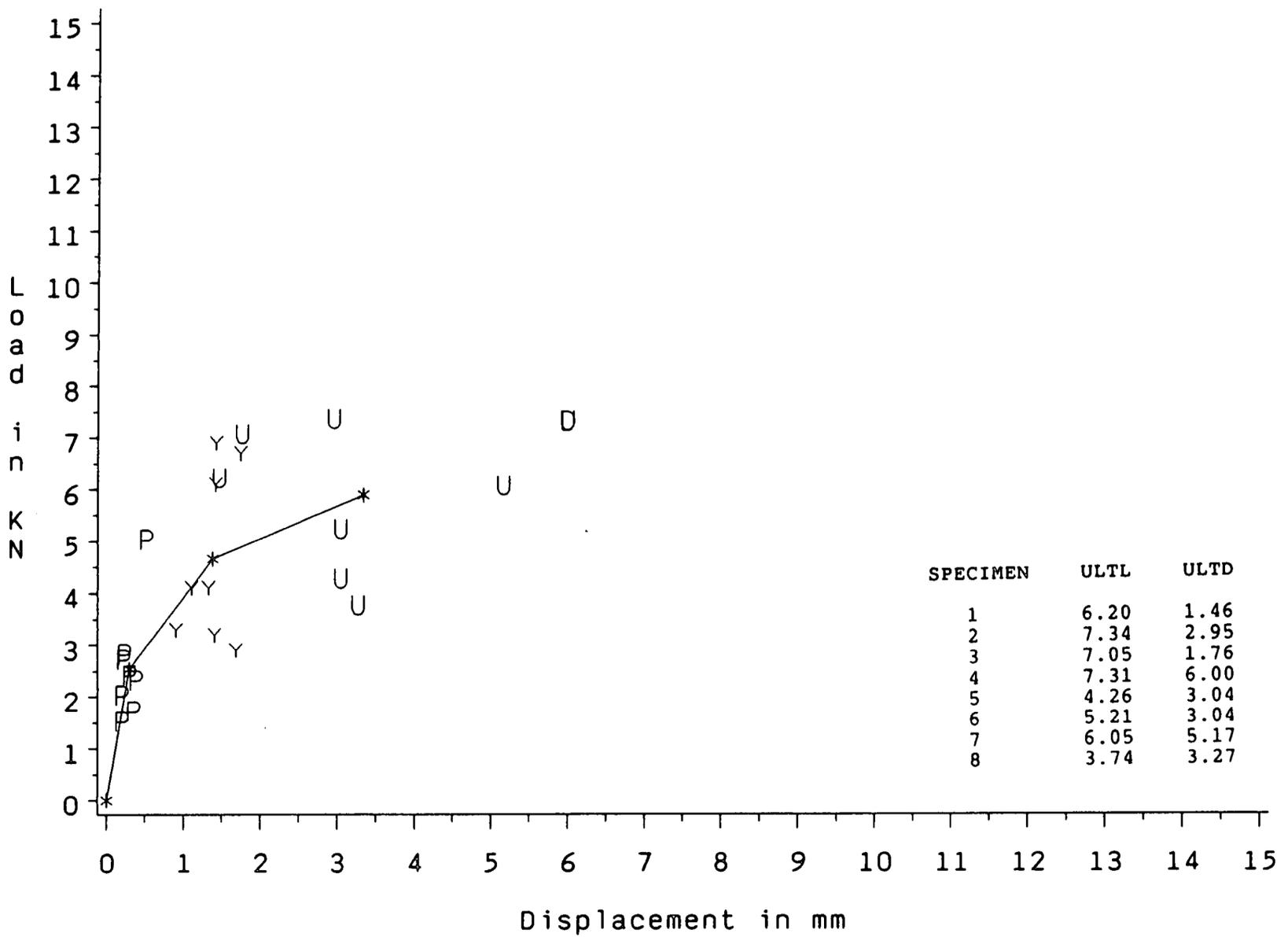
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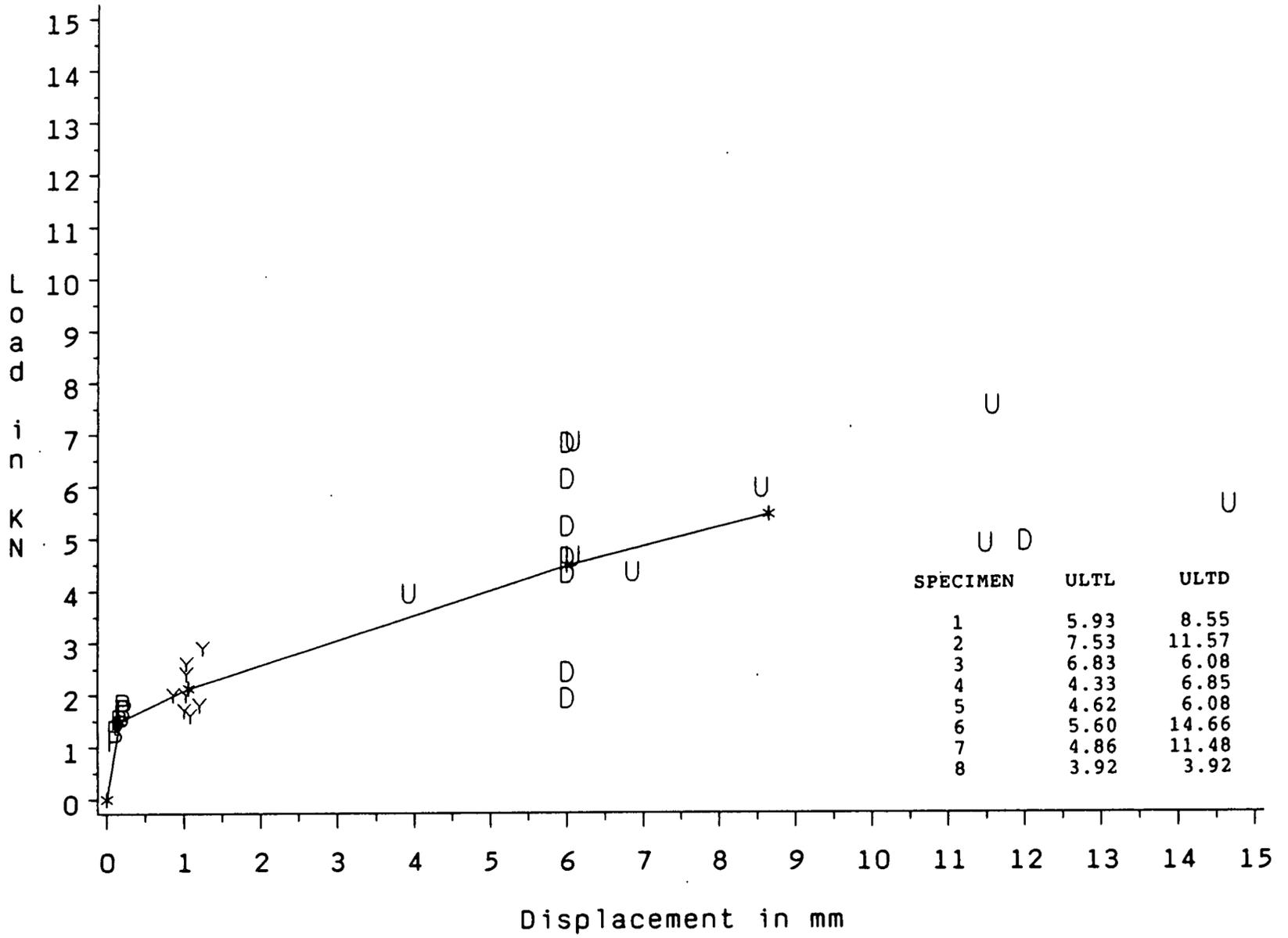
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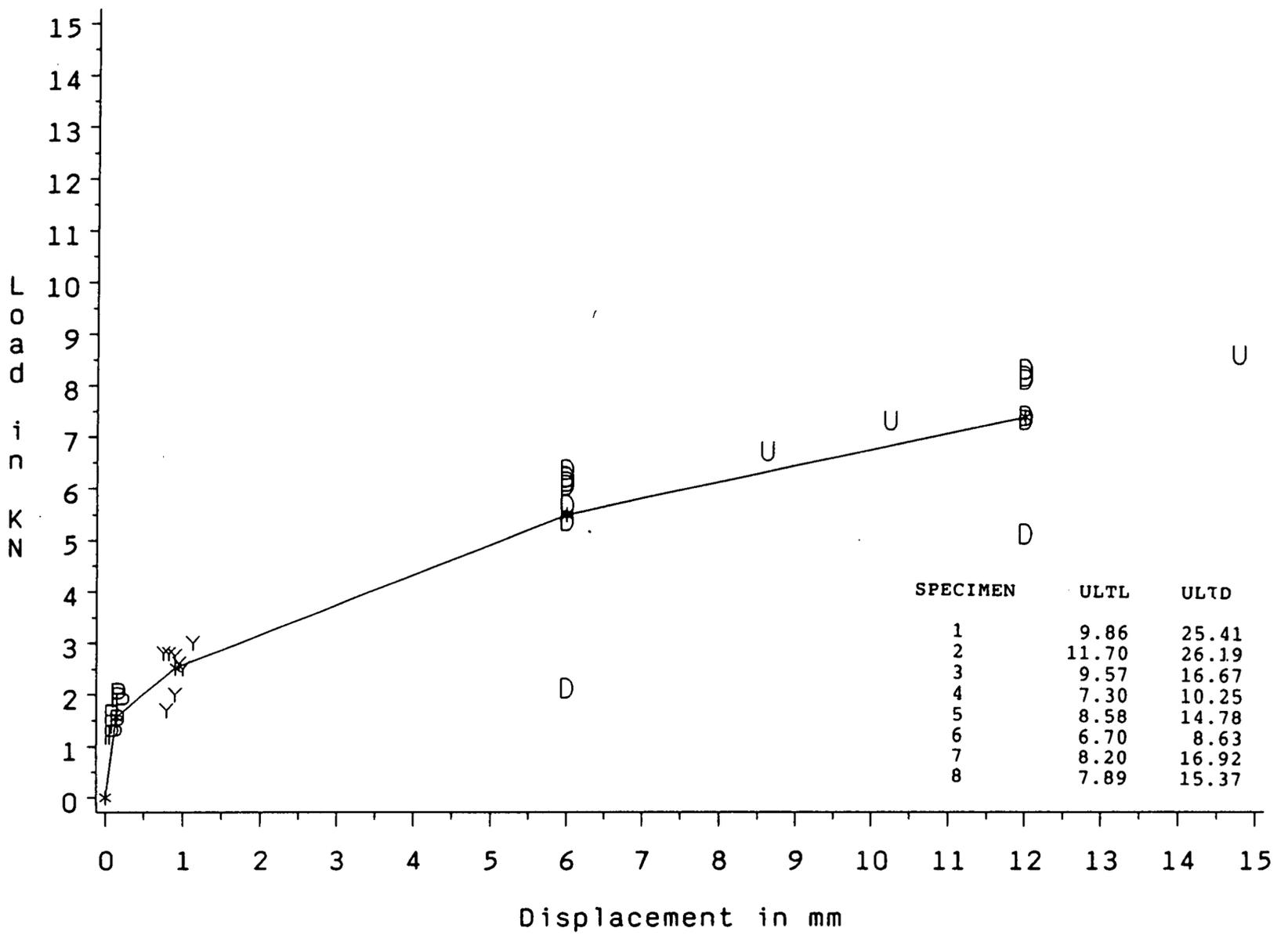
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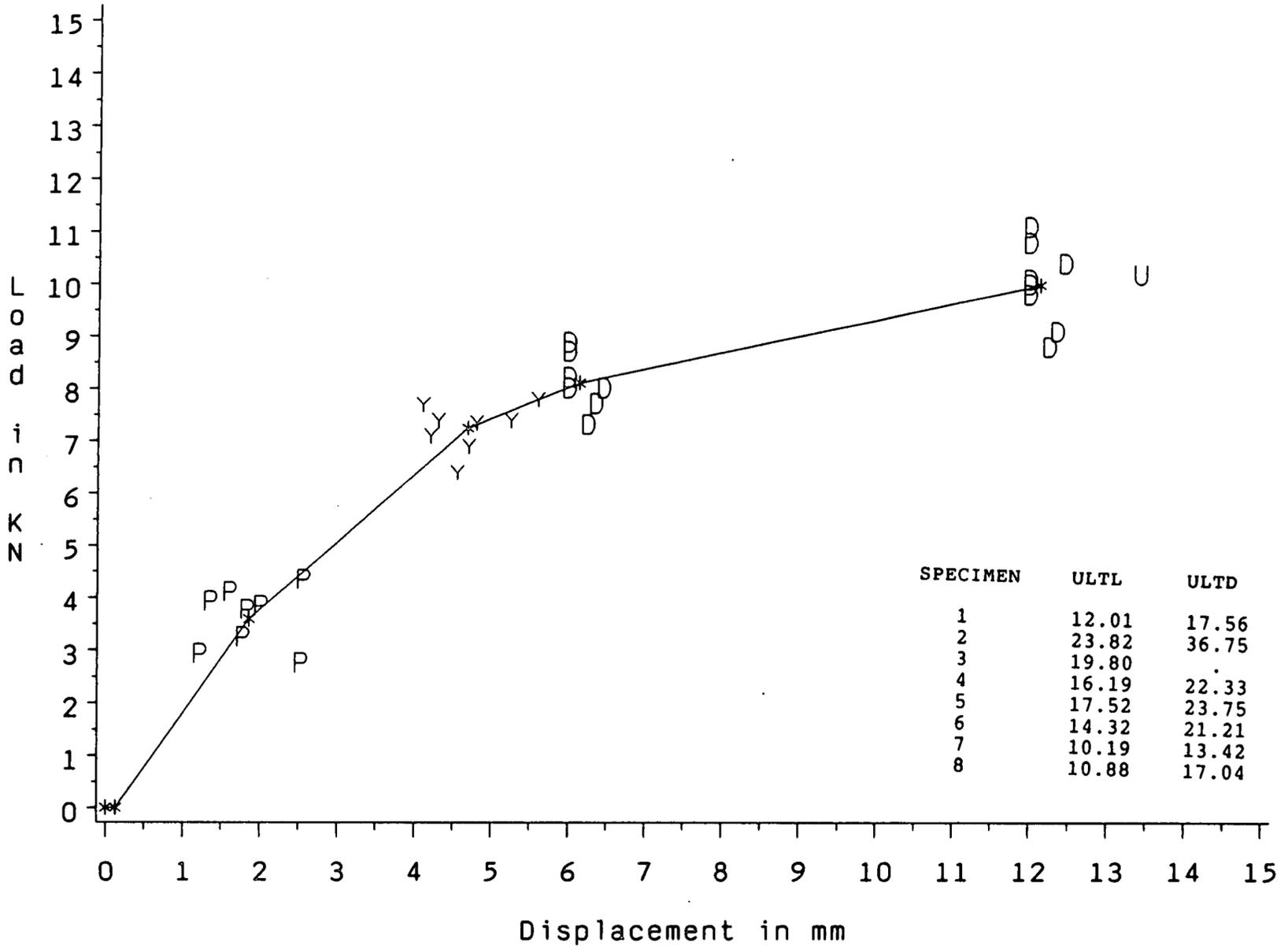
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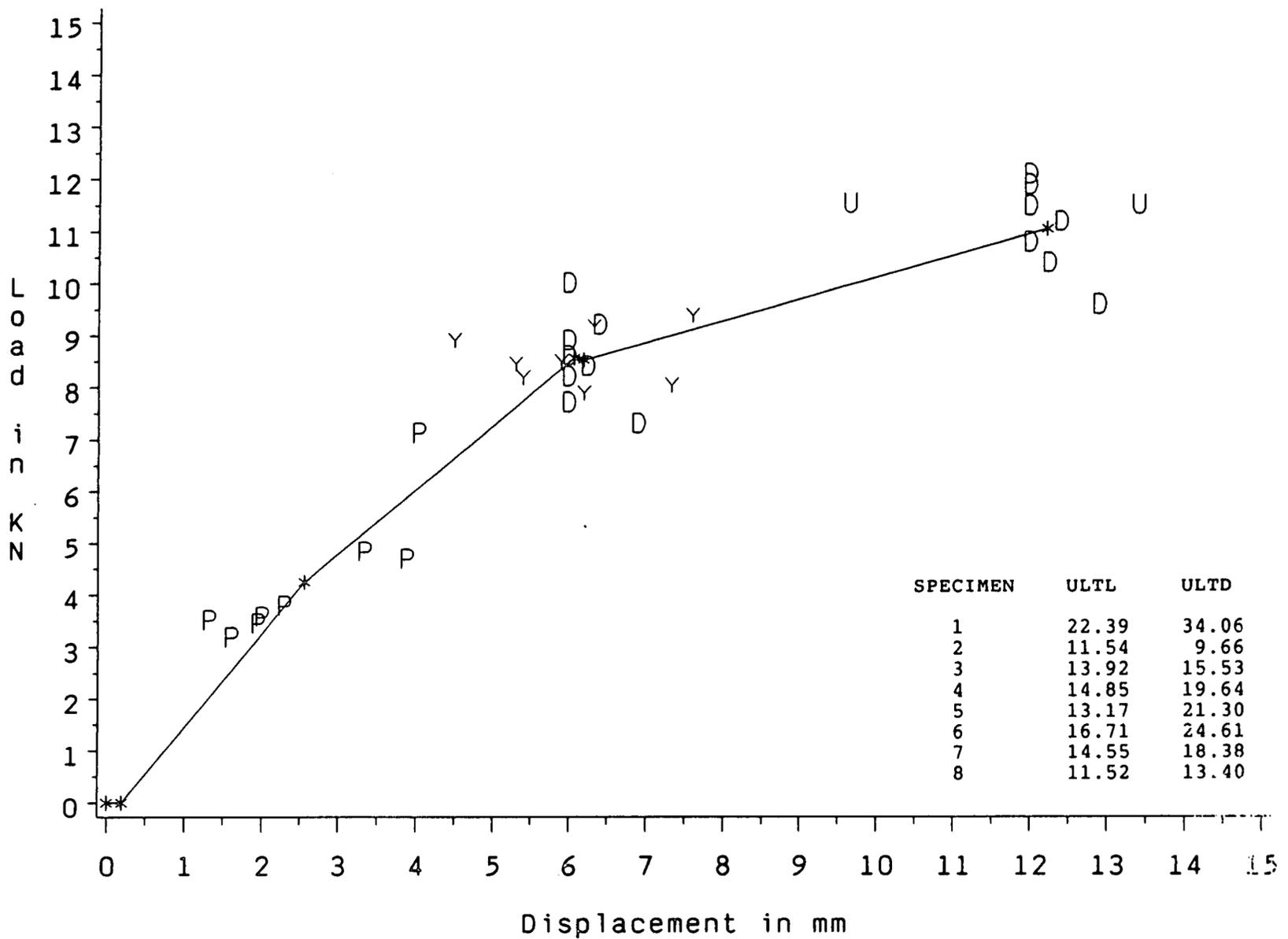
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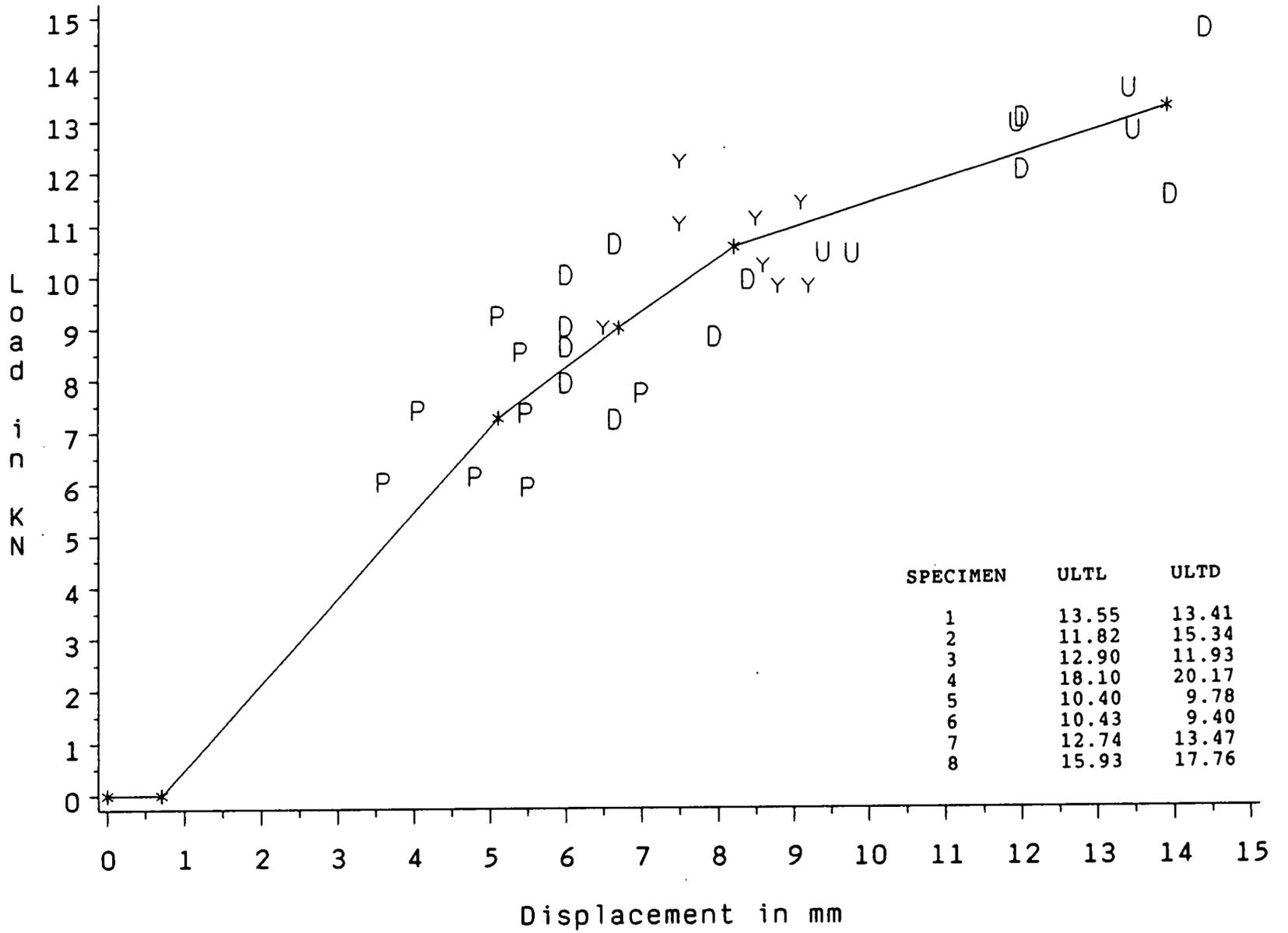
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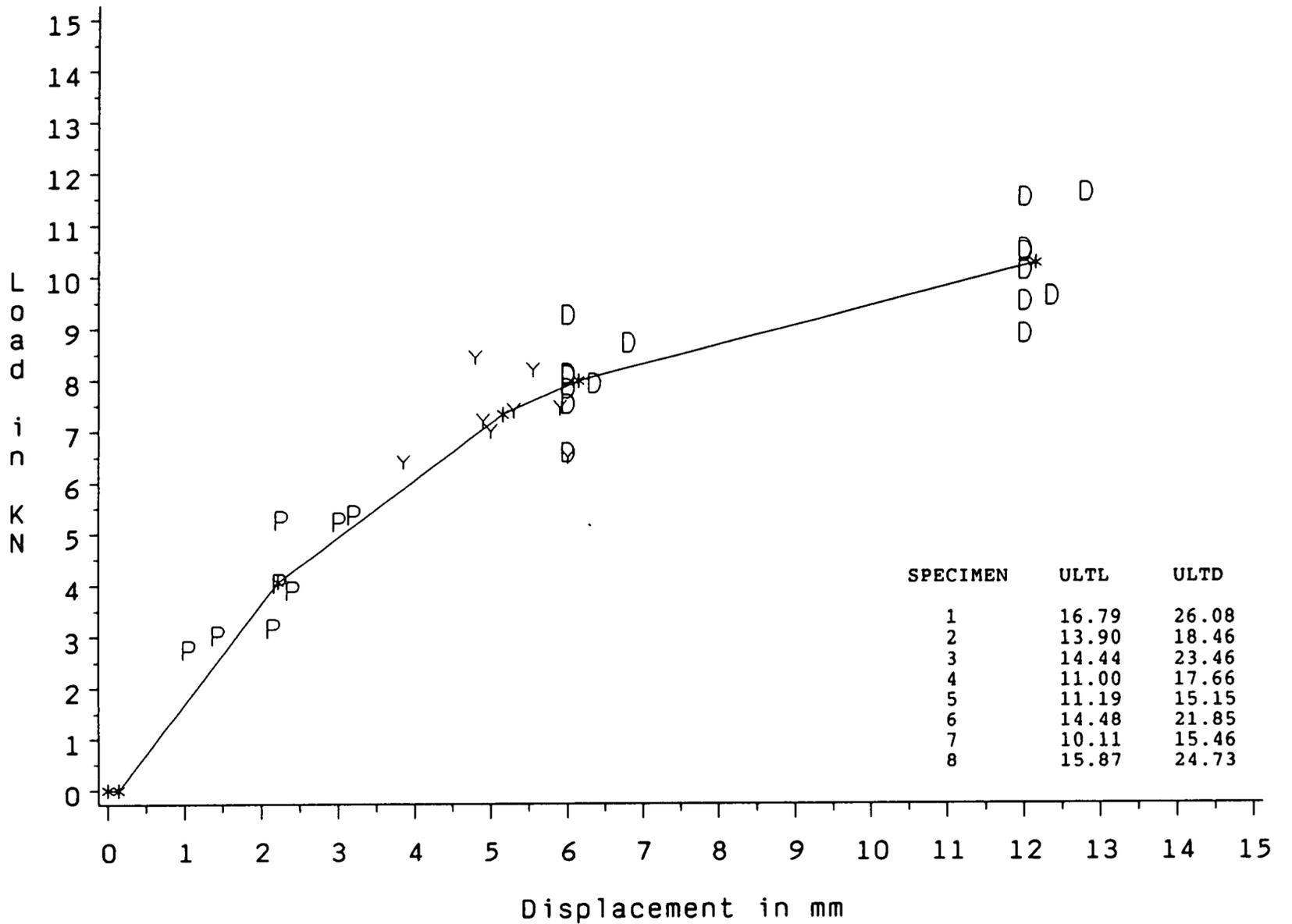
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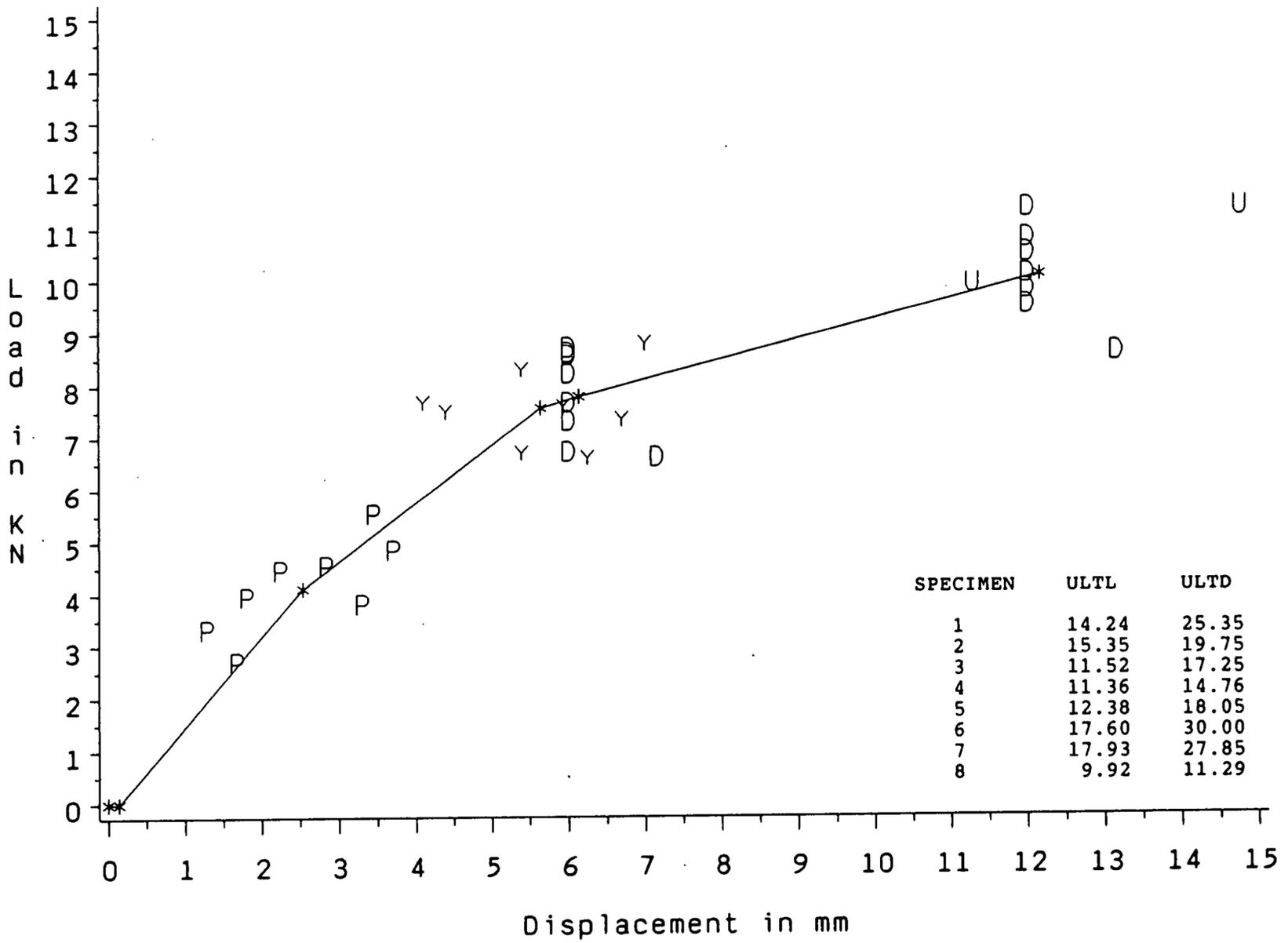
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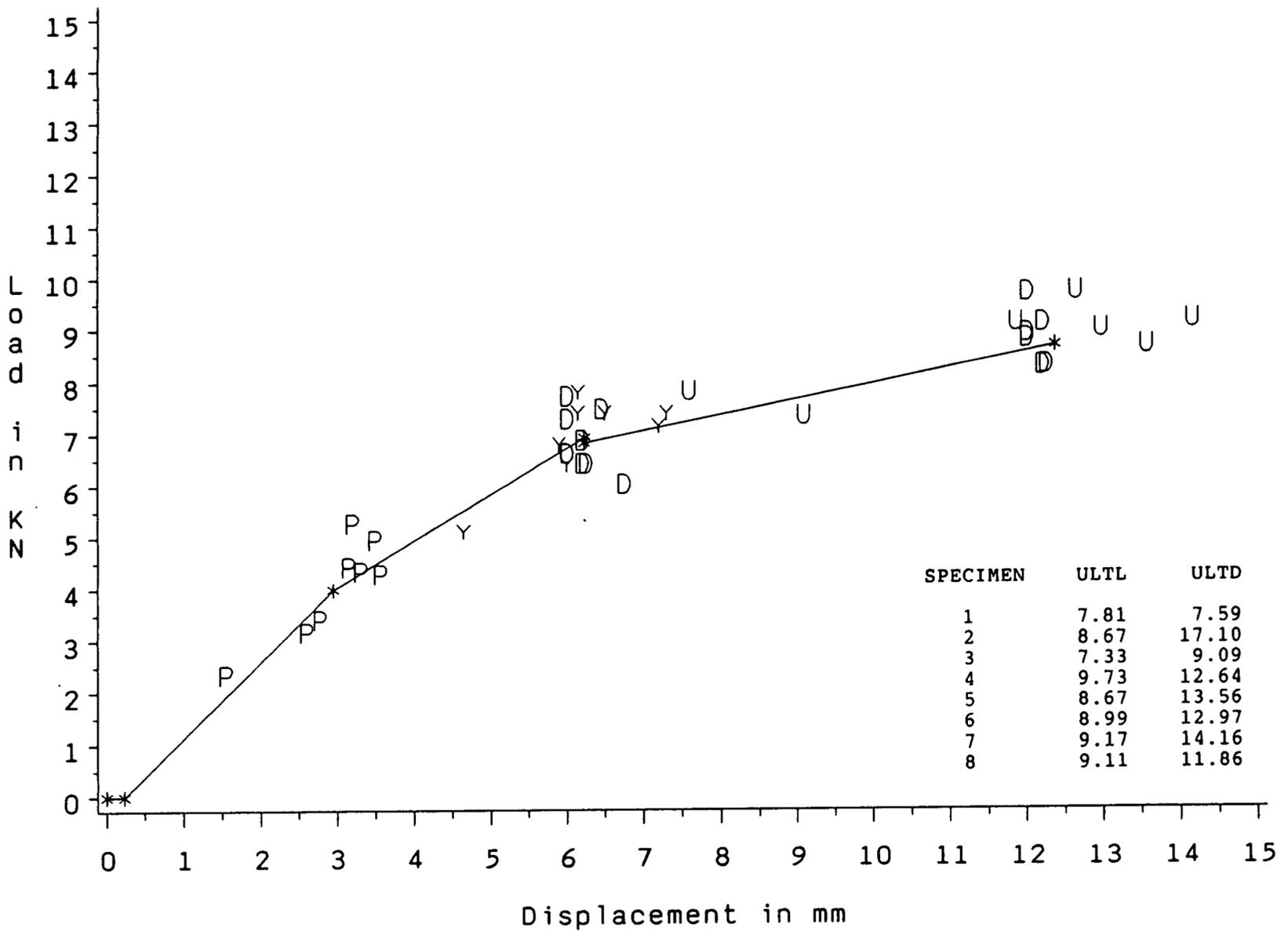
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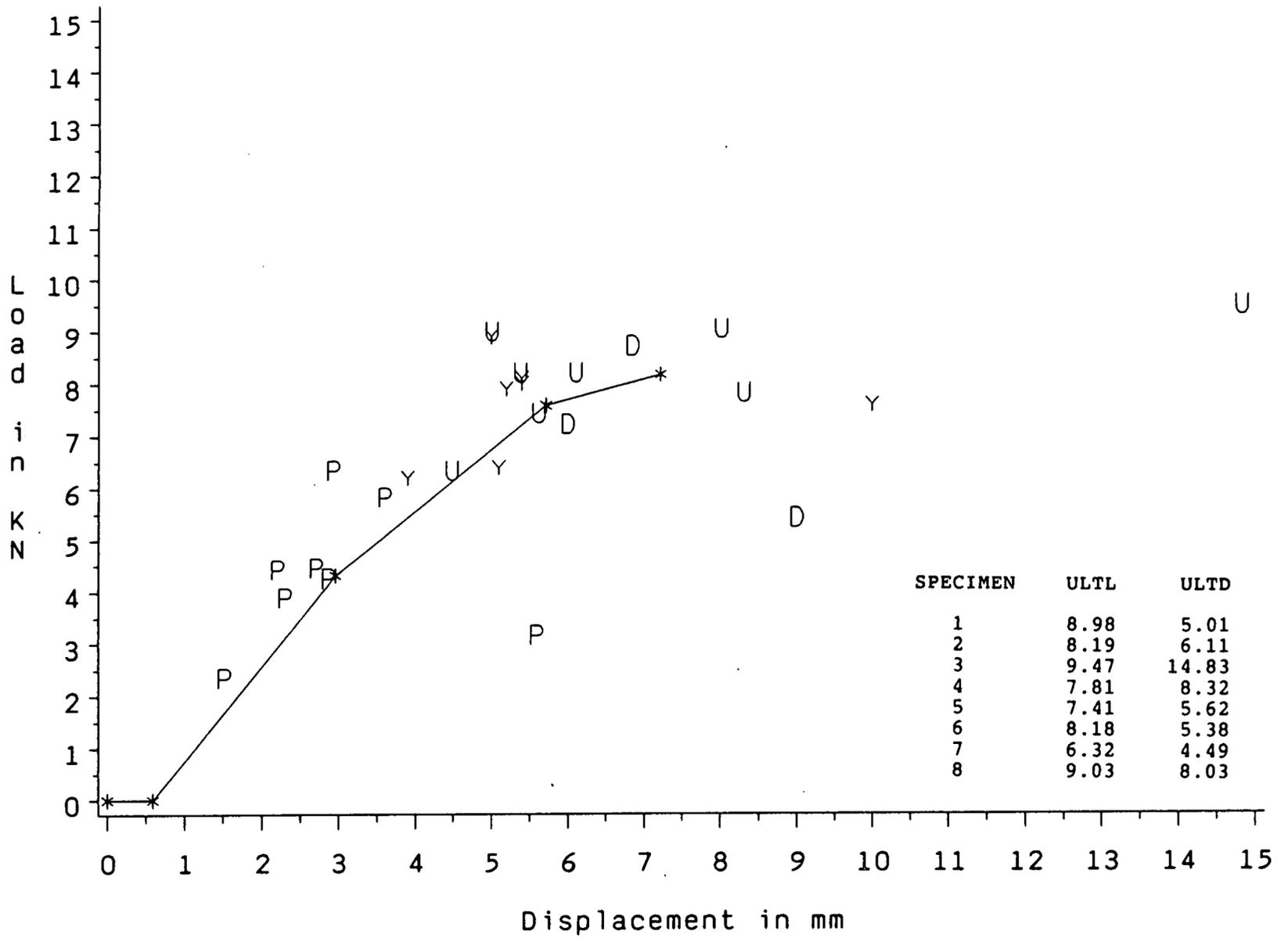
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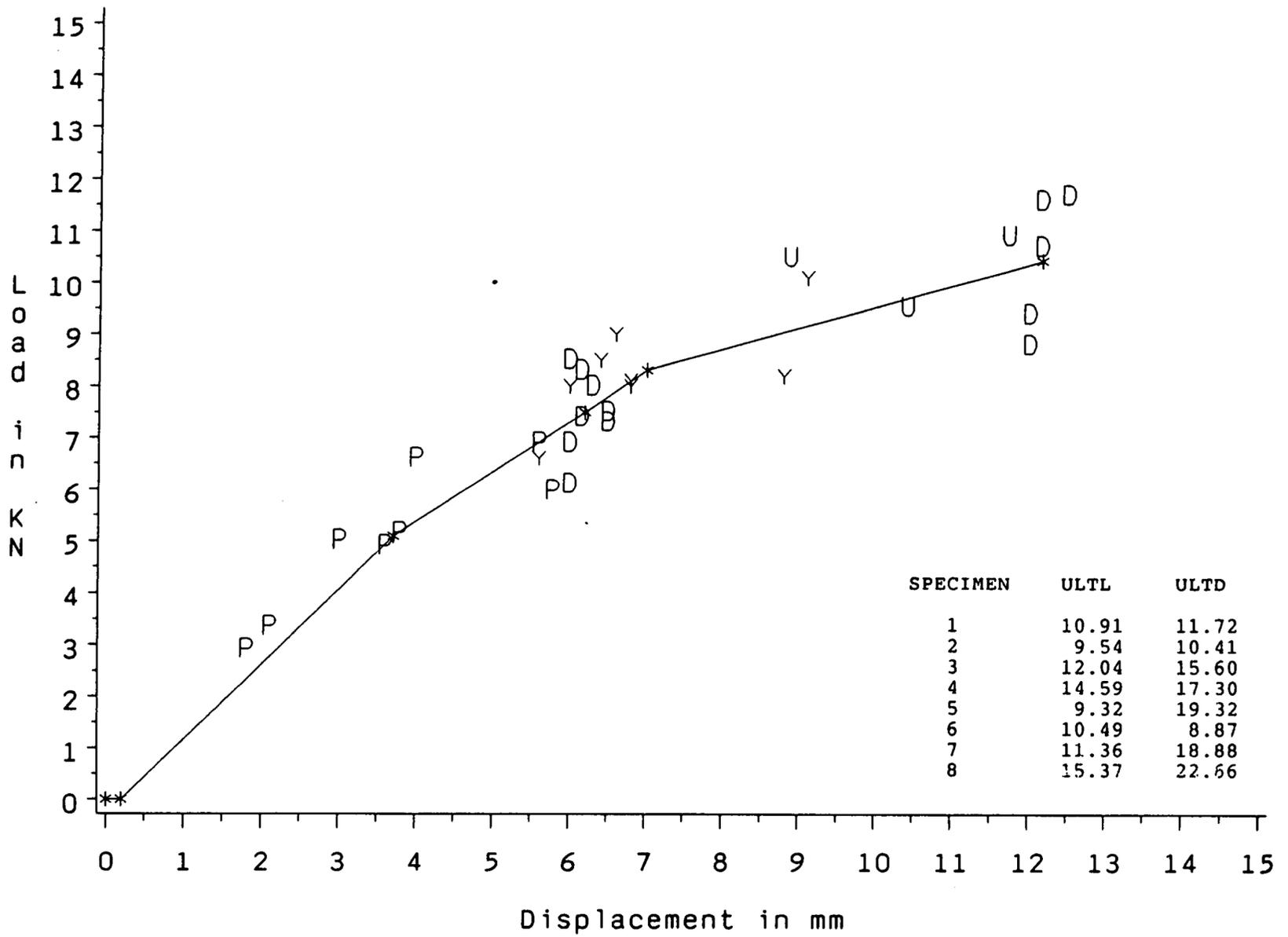
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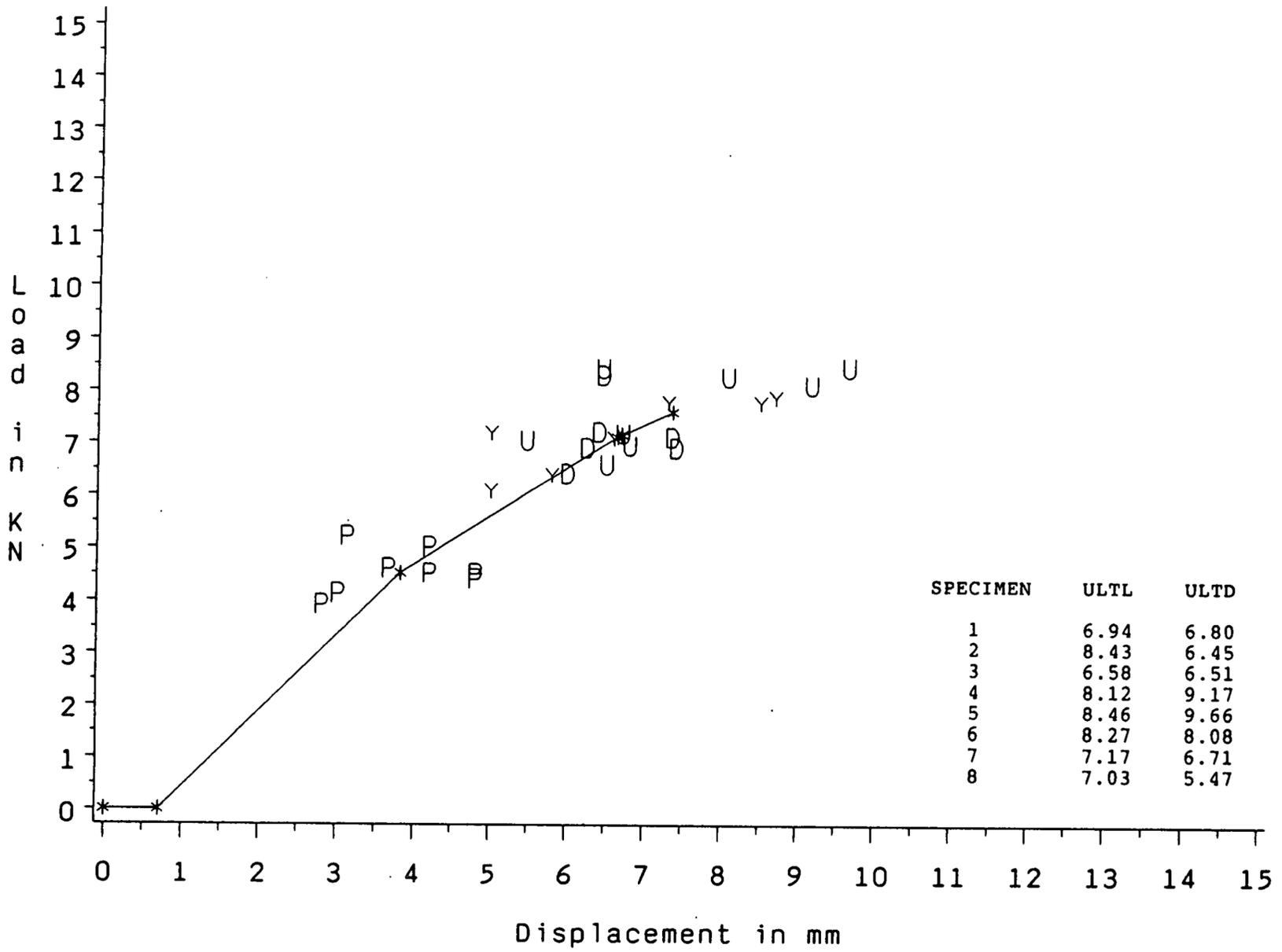
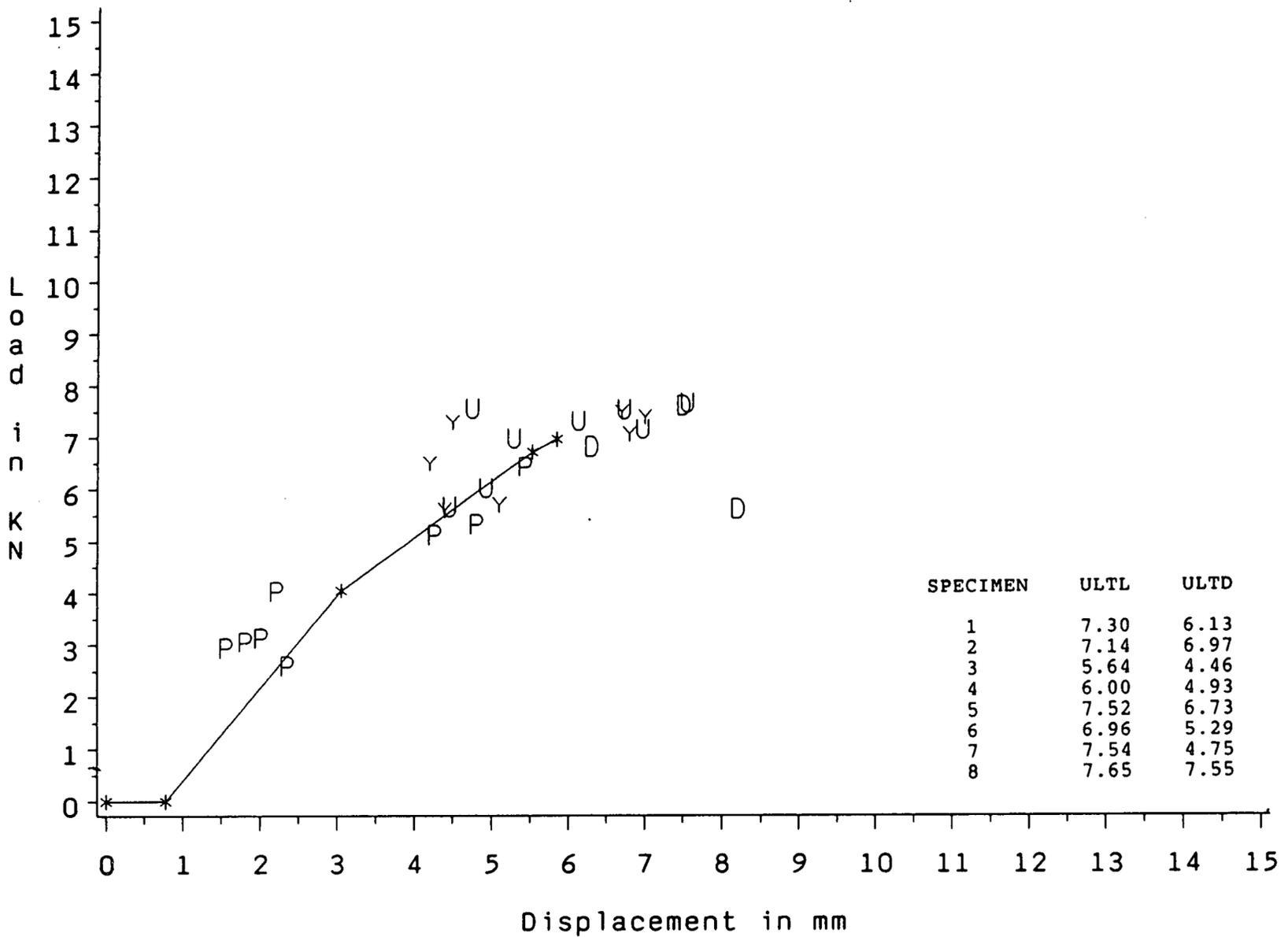


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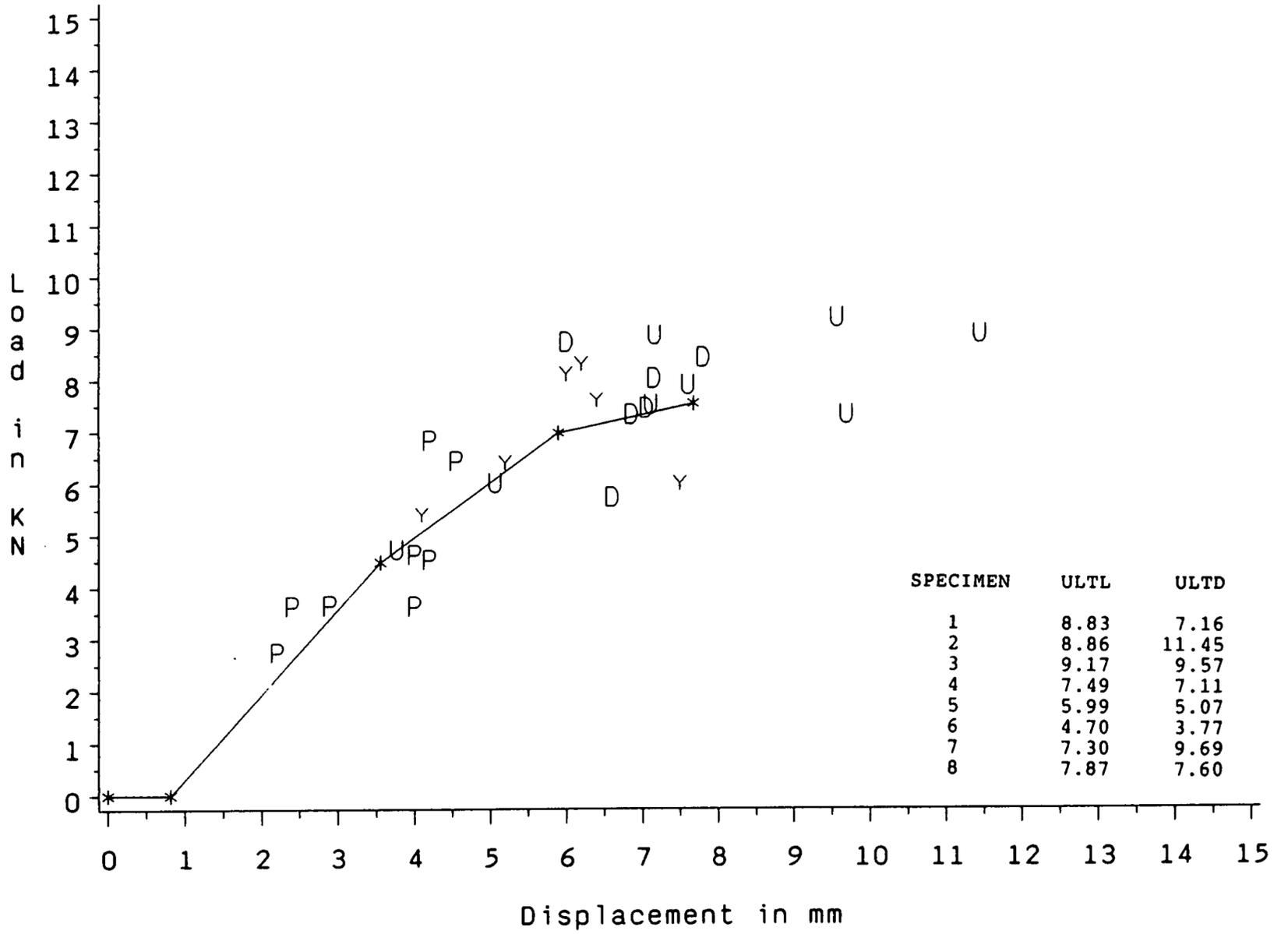


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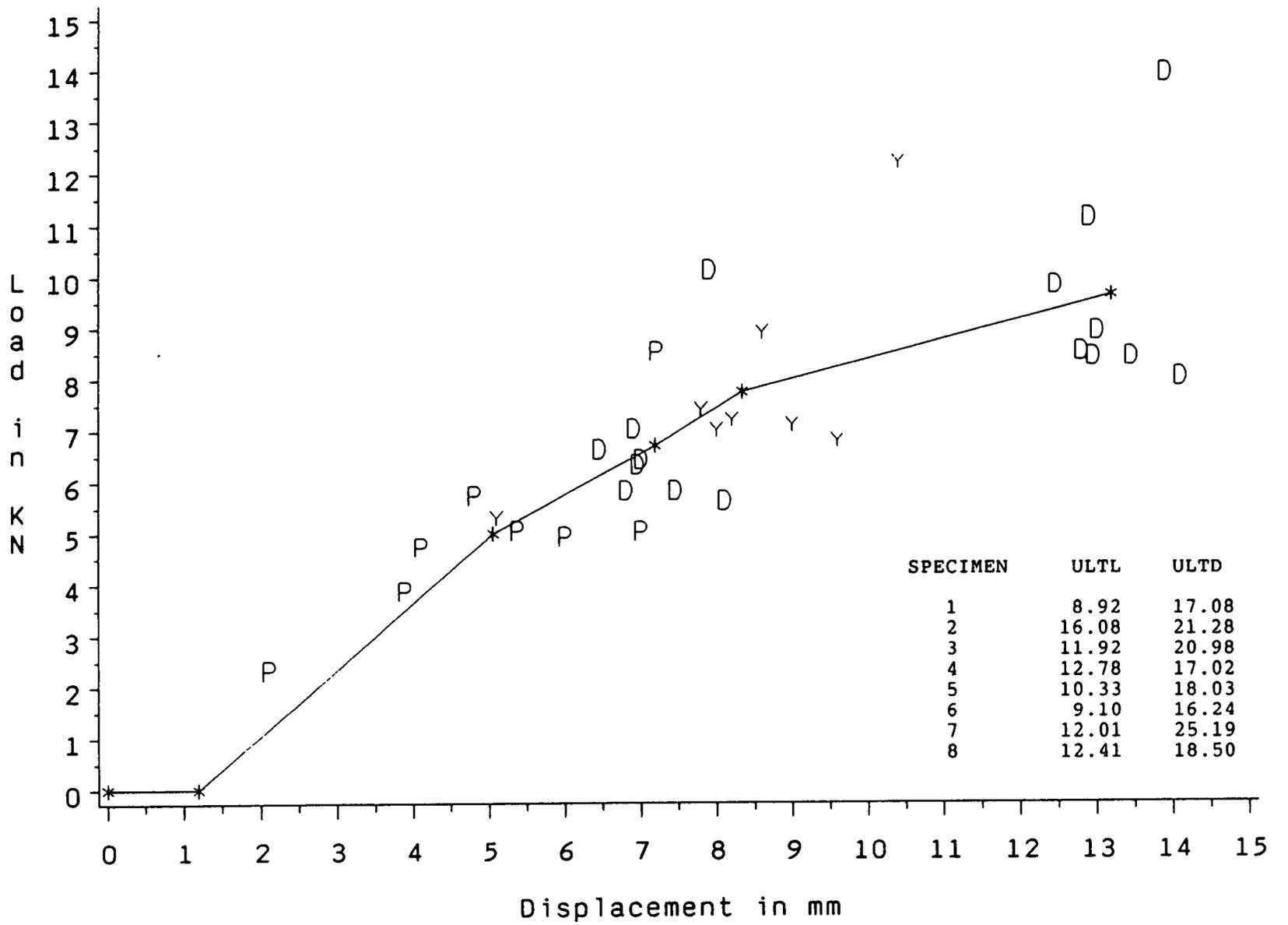


Joint code=eBCEJoint code=eBDE

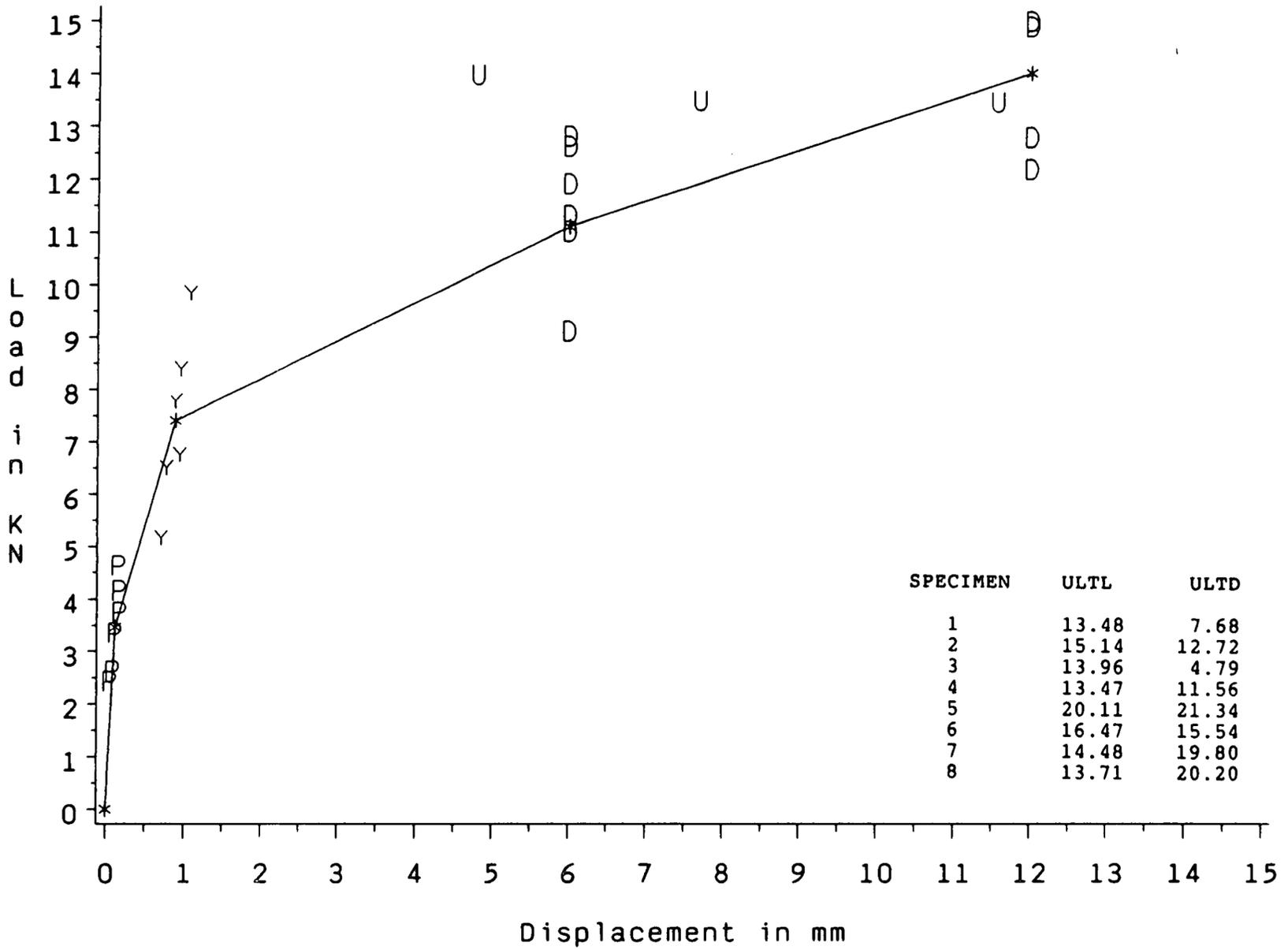
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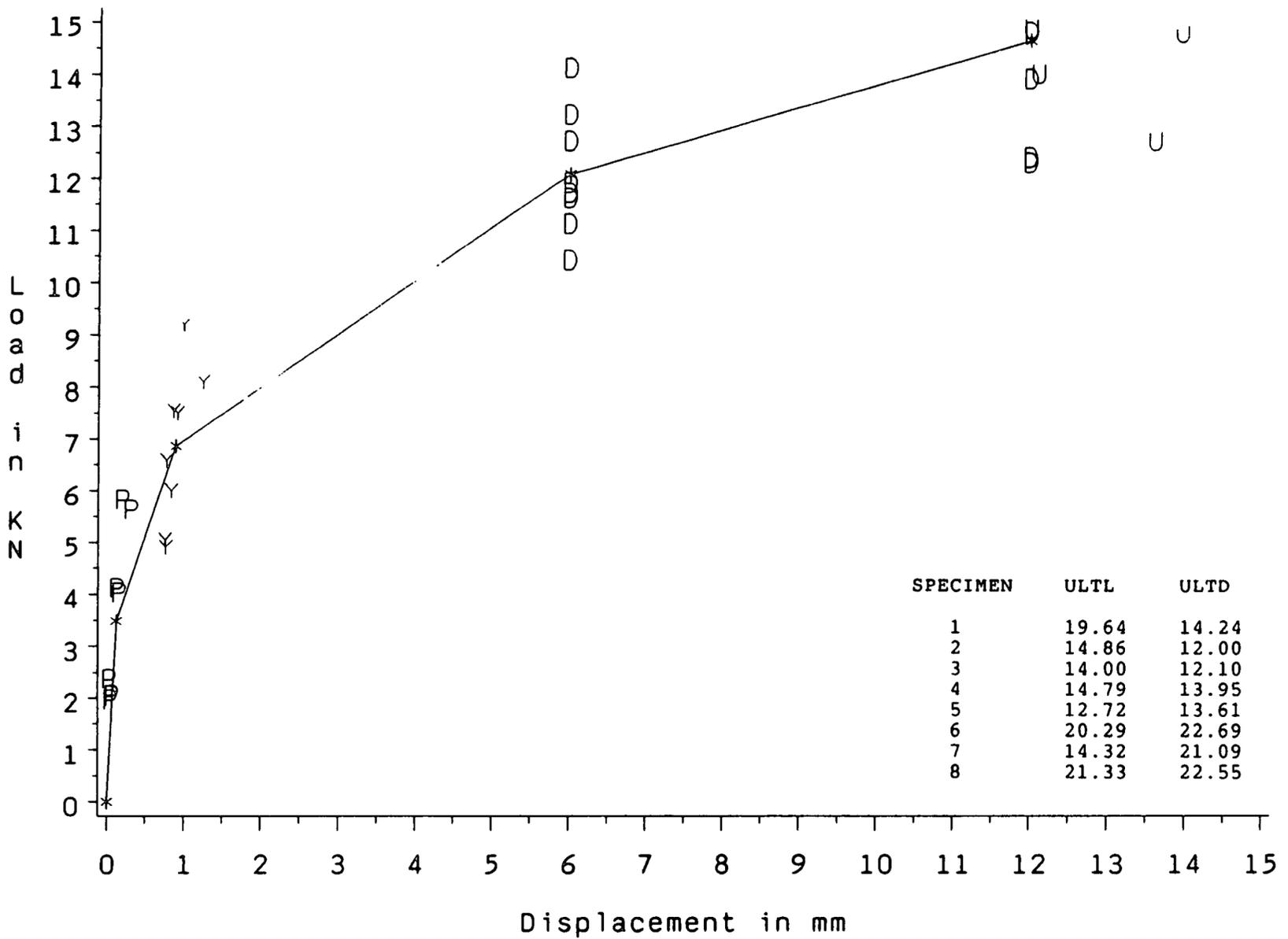
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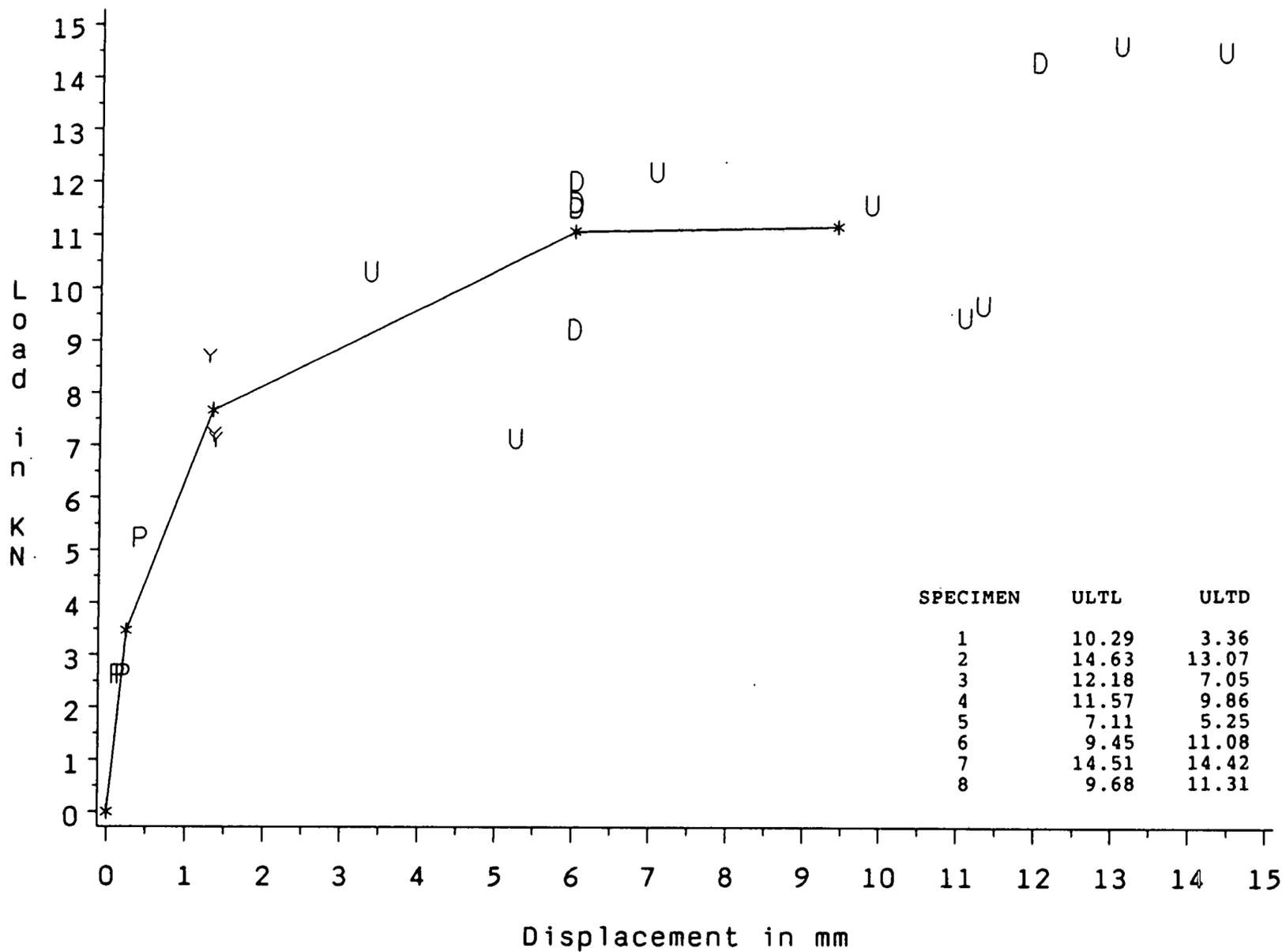
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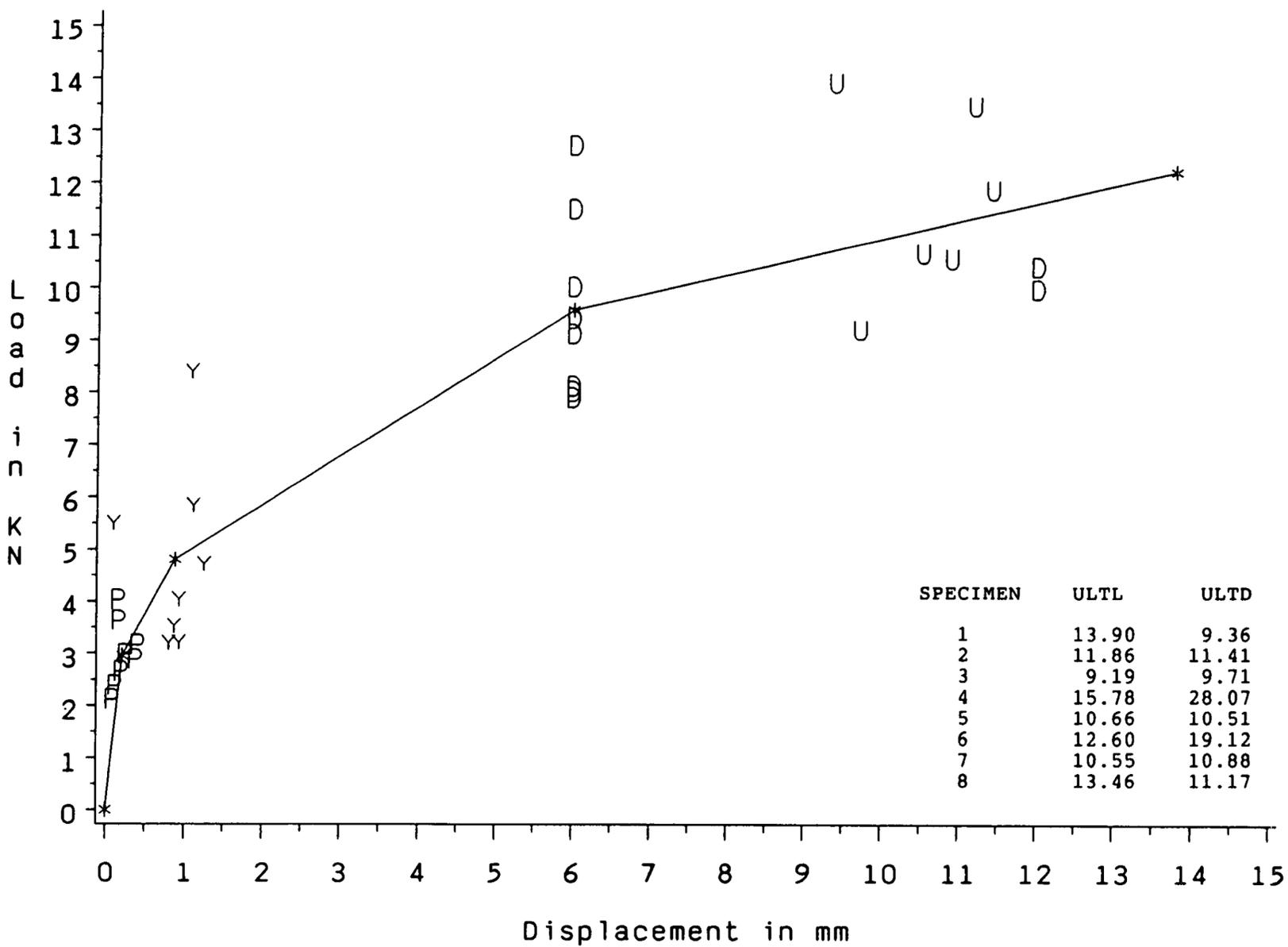
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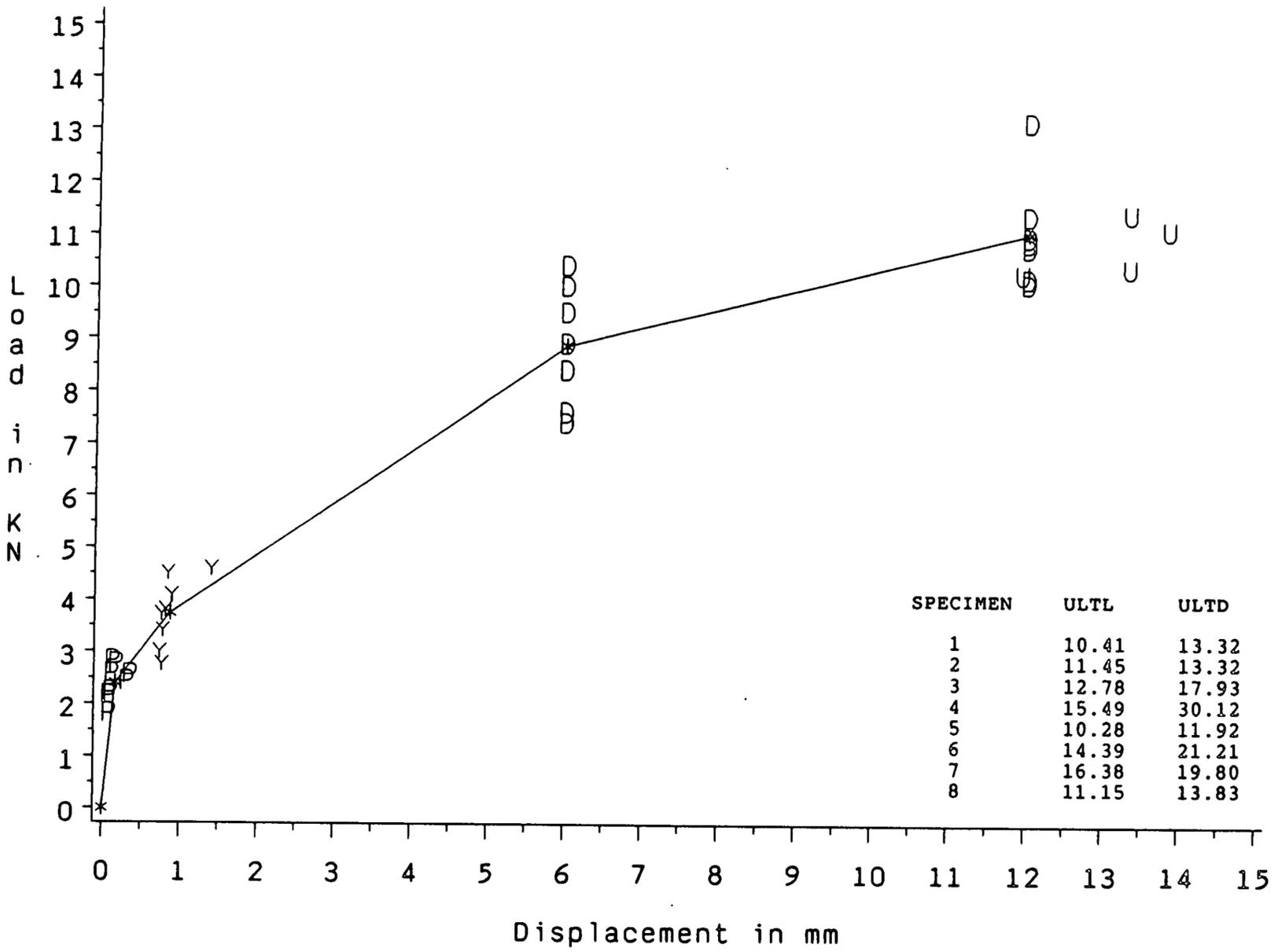
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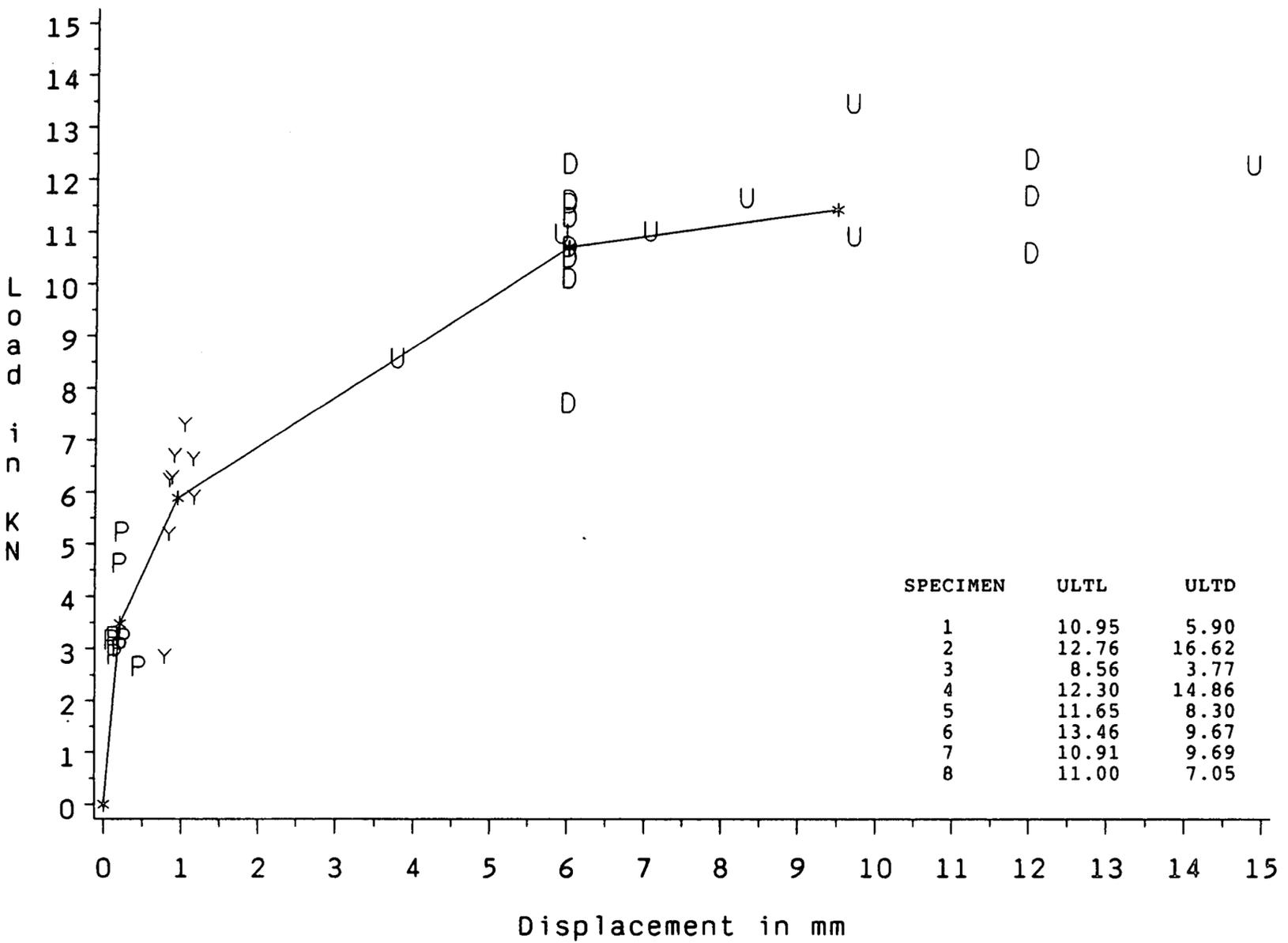
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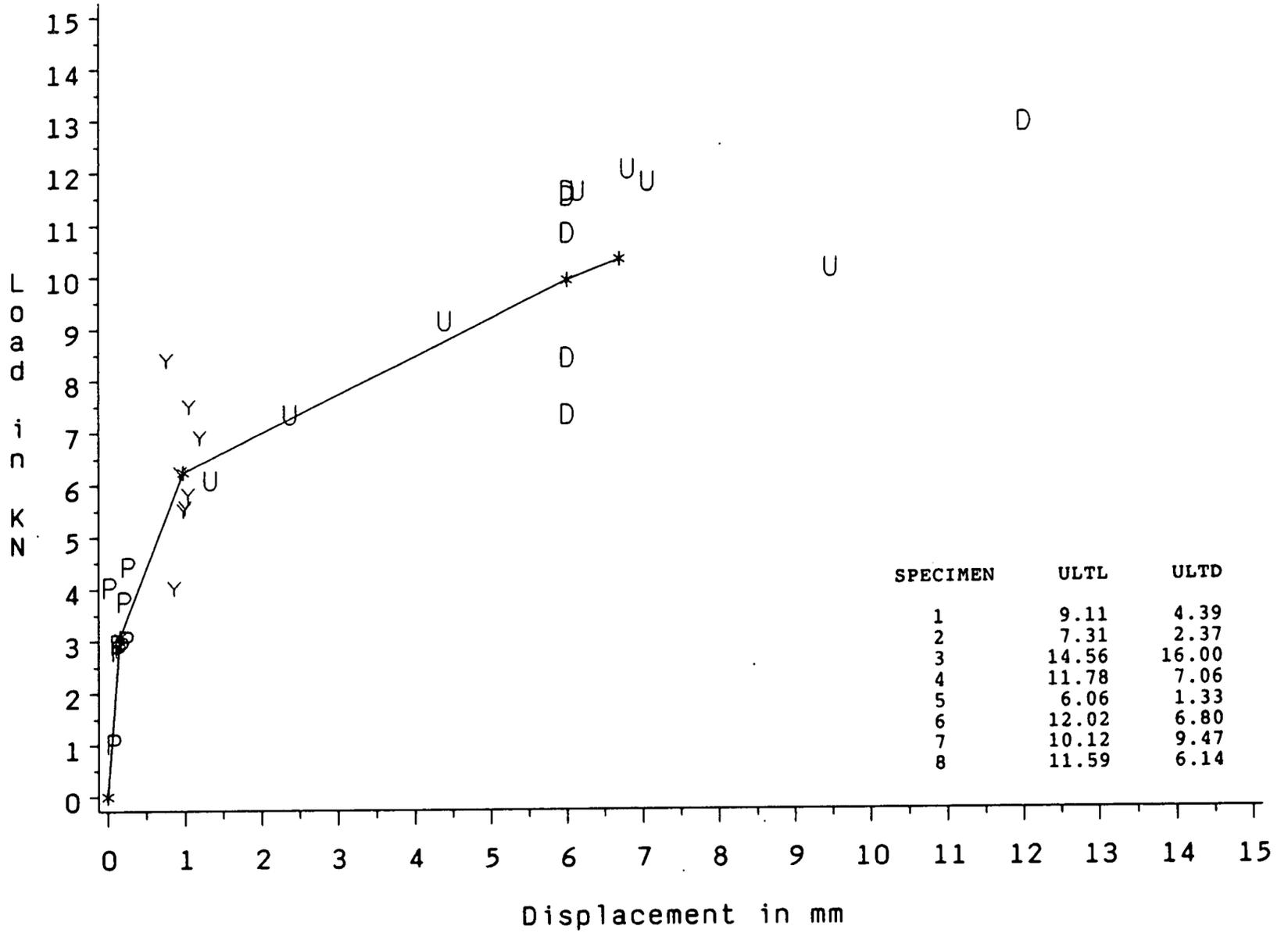
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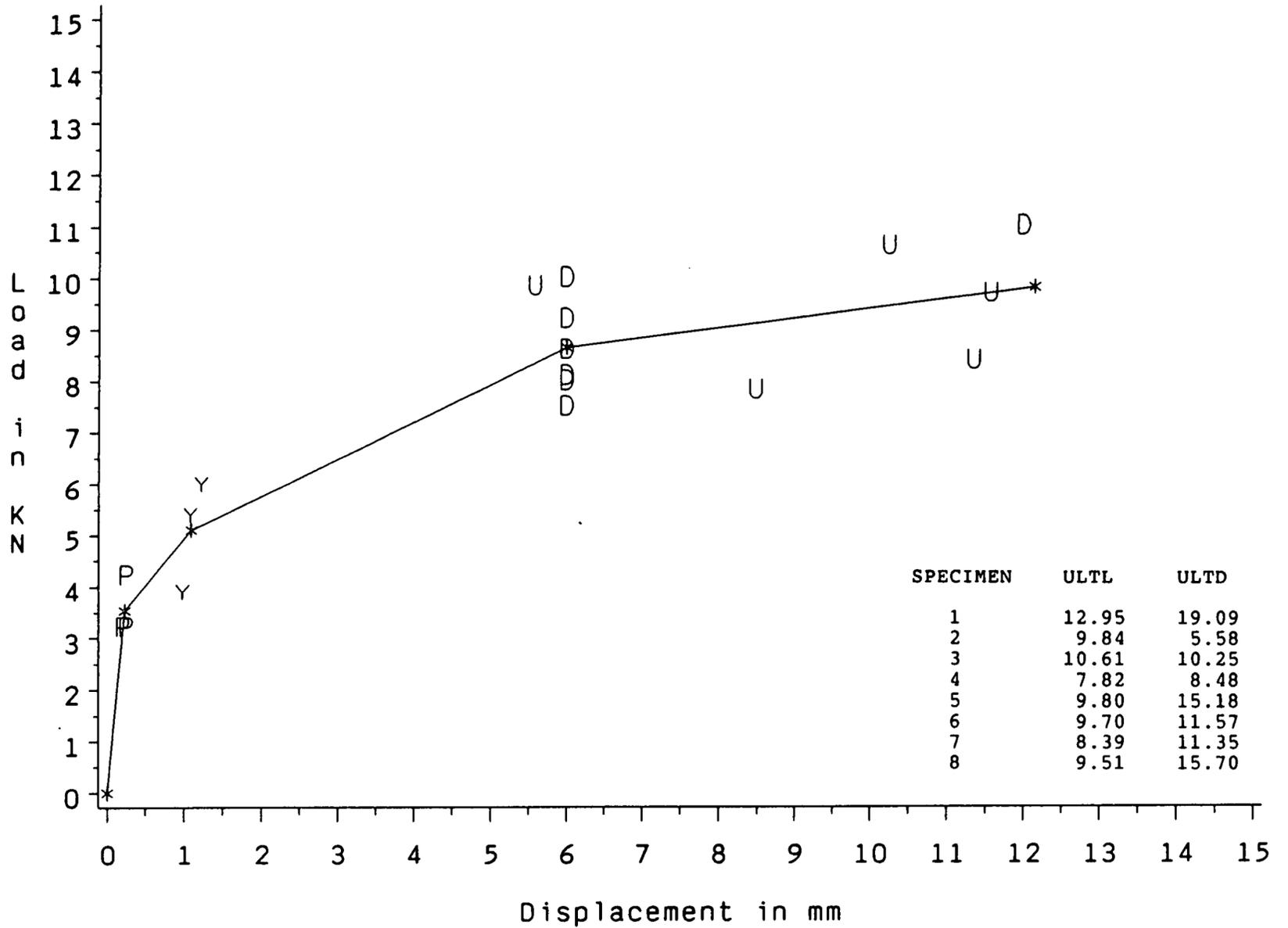
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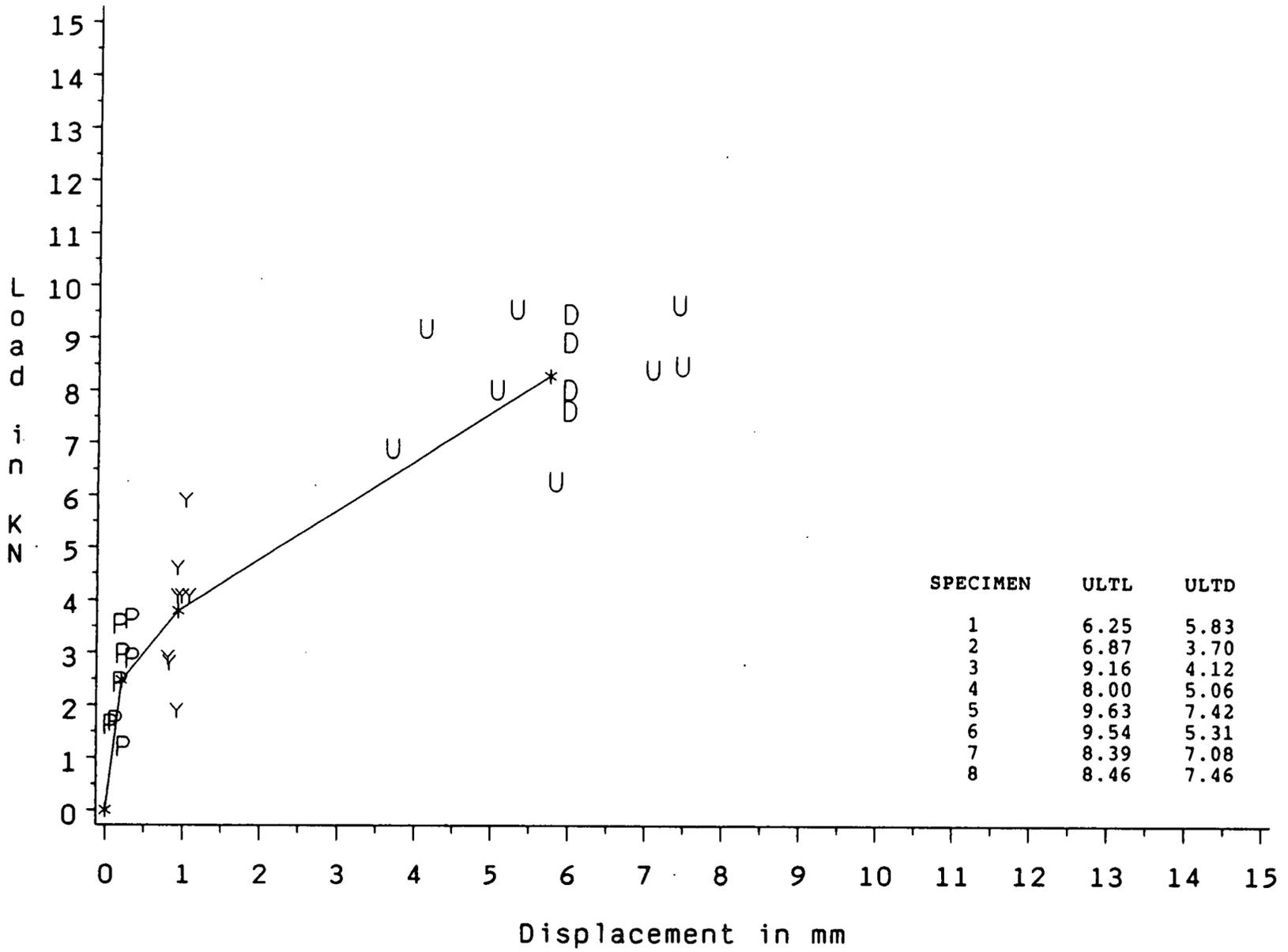
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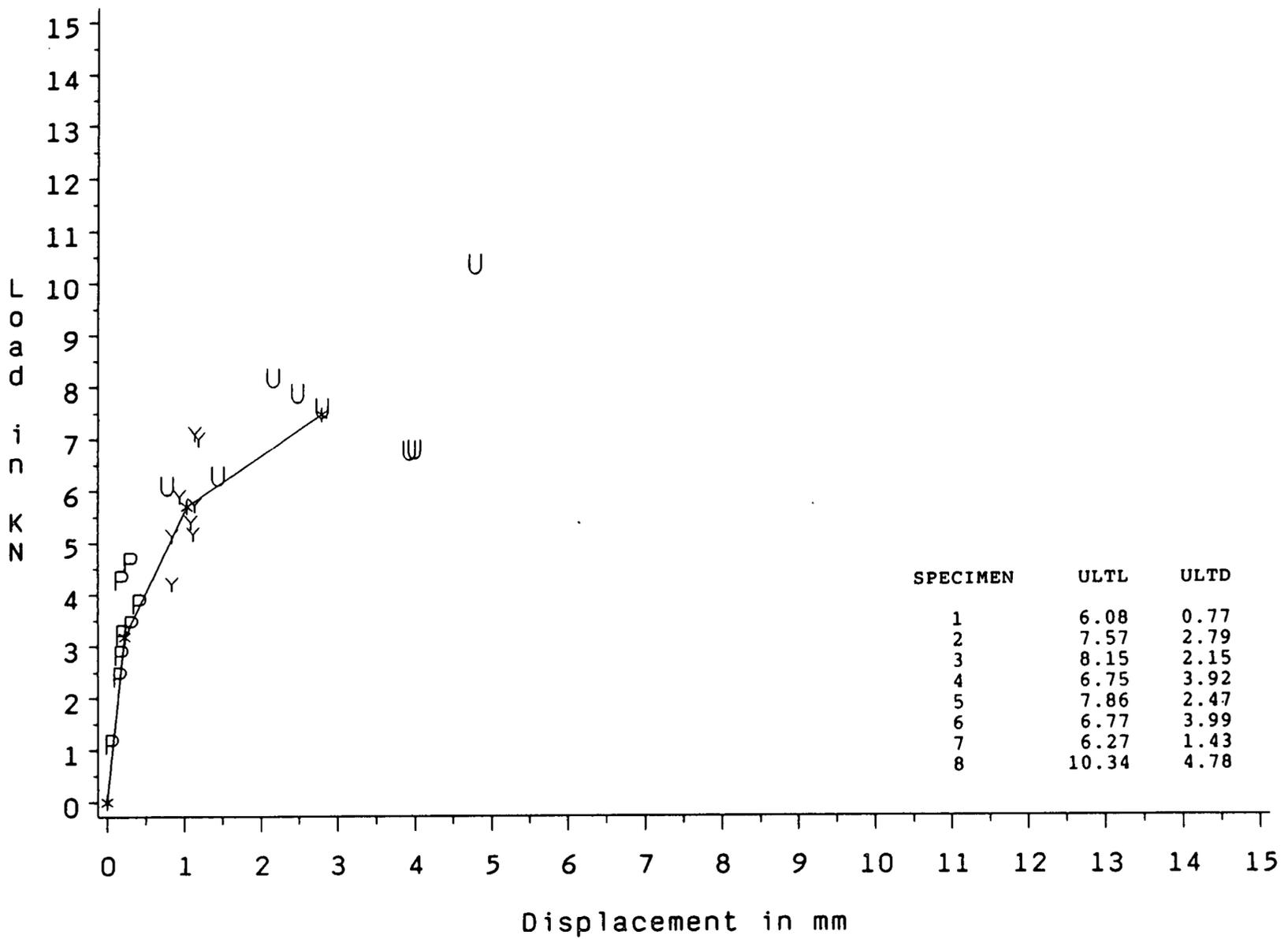
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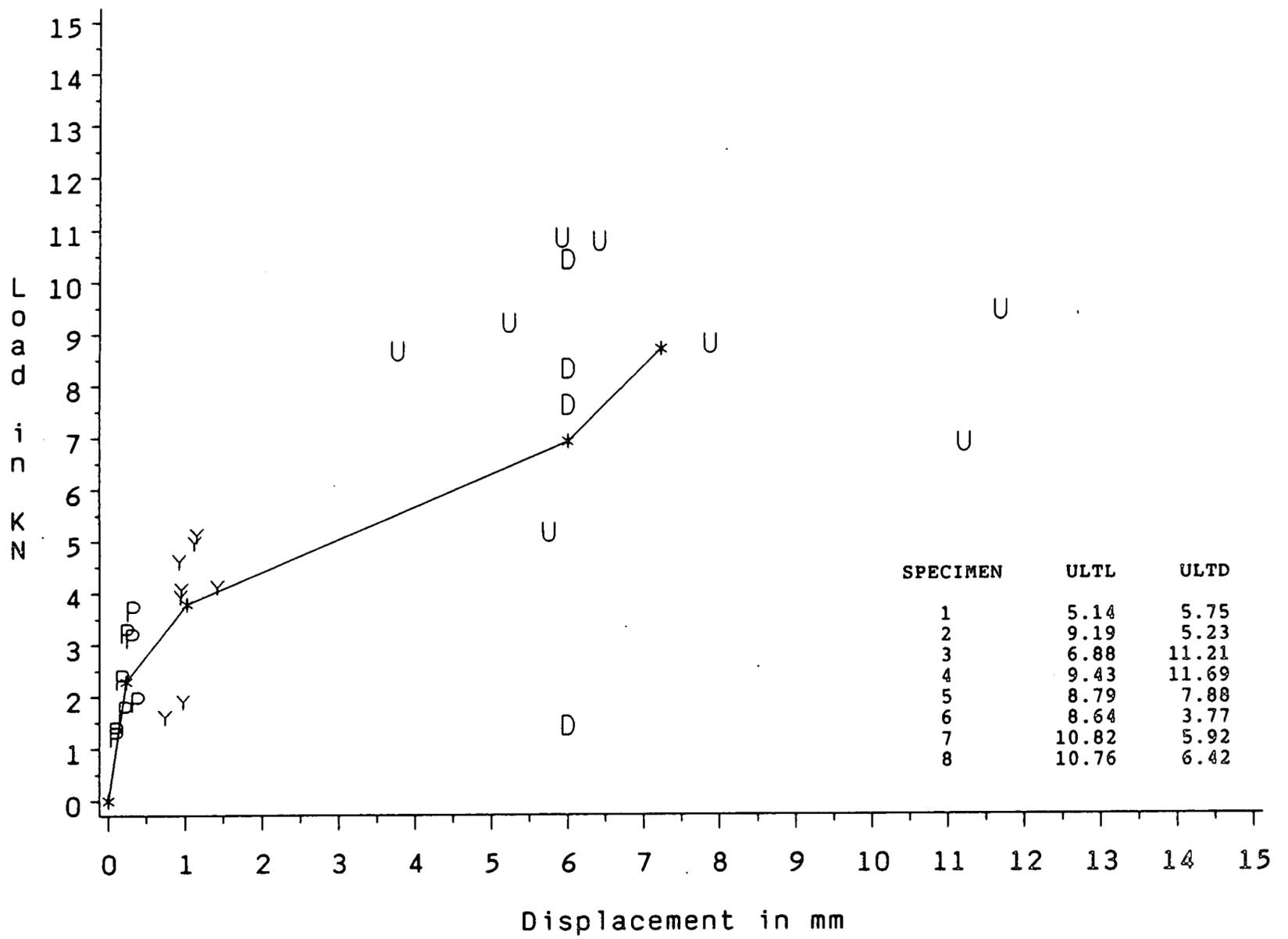
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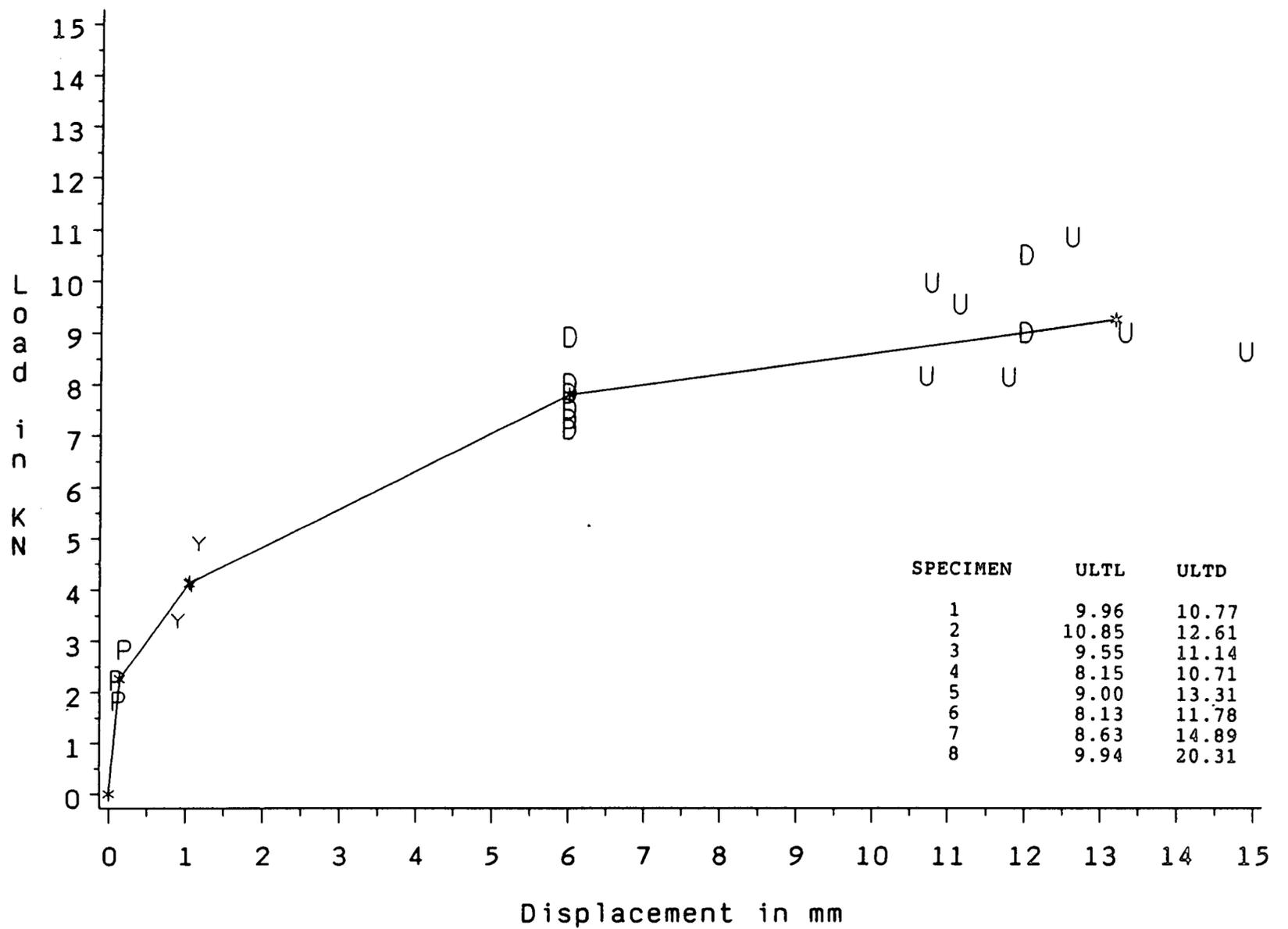
Joint code=fBDE



Joint code=fBC1E



Joint code=fBAC1



APPENDIX 7 KEY TO JOINT CODES**1. Groups Tested**

- a. Parallel to the grain, assembled wet tested wet.
 b. Parallel to the grain, assembled wet tested dry.
 c. Parallel to the grain, assembled dry tested dry.

- d. Perpendicular to the grain, assembled wet tested wet.
 e. Perpendicular to the grain, assembled wet tested dry.
 f. Perpendicular to the grain, assembled dry tested dry.

2. Variation Codes

O Code Joint	Variation (Code Requirement Tested)			
	Parallel to the grain		Perpendicular to the grain	
A Timber Thickness	50mm	(100mm)	50mm	(100mm)
B Bolt Hole	15mm	(13mm)	15mm	(13mm)
C Washer	32mm dia	(50mm sq)	32mm dia	(50mm sq)
C1 Coach bolt	coach	(50mm sq)	coach	(50mm sq)
D Edge Distance	2D=24mm	(2D=24mm)	2.5D=30mm	(4D=48mm)
E End Distance	4D=48mm	(7D=84mm)	4D=48mm	(300mm)
E1 Intermediate End Distance	5.5D=66mm	(7D=84mm)	not tested	

3. Combinations Tested

Parallel to the grain			Perpendicular to the grain		
a O	b AO	c AO	d O	e O	f O
a B	b AB	c AB	d B	e B	f B
a BA	b ABC	c ABC	d BA	e BA	f BA
a BC	b ABC1	c ABC1	d BC	e BC	f BC
a BC1	b ABE	c ABE	d BC1	e BC1	f BC1
a BE	b ABE1	c ABE1	d BD	e BD	f BD
a BE1	b ABCE	c ABCE	d BE	e BE	f BE
a BAC	b ABCE1	c ABCE1	d BAD	e BAC	f BAC
a BAE			d BCE	e BCE	f BCE
a BCE			d BDE	e BDE	f BDE
a BACE			d BC1E	e BC1E	f BC1E
a BAC1			d BAC1	e BAC1	f BAC1

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