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SAN ANTONIO, TEXAS

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PHASE IV - INVESTIGATION OF STRENGTH OF ISOLATED VERTEBRAE

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SUMMARY

This report summarizes research conducted on isolated human vertebrae by Technology Incorporated during the year 1965-1966. The dynamic strength of specimens from portions of two human spines was determined. Relative dynamic strengths of centra versus intervertebral discs were measured. The results are presented as a series of graphs which compare experimental values with those found in the literature.

INTRODUCTION

The causes of spinal fractures are of both present and future interest in aerospace technology. At present, aircraft ejections and crash landings persistently result in fractures. For the future, designs of aircraft and space vehicles are under consideration in which impact acceleration of the human body along its spinal, or G_z axis is expected. This may be a regular occurrence, as in delta platforms and lifting bodies which touch down at a high angle of attack, or an emergency, such as the settling of vertical take-off aircraft and, in the event of a power loss, during lunar landings.

Whether or not spinal fracture will occur as a result of the impact in an operational case such as one of those above is dependent upon a large number of factors. One group of these relates to the forces applied to the exterior of the body and acting to accelerate it: waveform, orientation, and area of application, including the initial conditions prior to impact. A second group relates to the transmission of these forces within the body: the mass, viscosity and elasticity of its parts. A third group relates to the factors governing fracture itself: the dynamic strength of each element of the spine. If force nowhere exceeds strength, then no fracture will occur; conversely, if the applied force is sufficiently excessive, one fracture may not attenuate it sufficiently to prevent the occurrence of others.

To build up a concept of how an applied force propagates along and possibly fractures the spinal column, a large body of data must be gathered and combined. These data are stiffness and strength measurements under conditions specified by the following pairs of words: axial, bending; static, dynamic; centrum, disc (e. g. static axial stiffness of the centrum).

Some of the required measurements presently exist in the literature in the form of numerical values of satisfactory accuracy. This is the case especially for static stiffness and strength.

Strength under static conditions has been measured by a number of investigators, among whom Ruff (1950) has contributed the greatest number of measurements. His data shows that the strengths of vertebrae decrease with position upward along the spine; the lowest, or 5th, lumbar is the strongest. While Ruff worked with groups of three or more vertebrae, Nachemson (1960) performed a few tests on groups of two vertebrae and one disc. His specimens included two from young adults, and these yielded values higher than those of Ruff. Perey (1957) tested groups of 1, 2, and 3 vertebrae. His specimens were generally from older persons, and gave lower values. Of the three, Perey was alone in providing dimension or area data by which the strength of vertebrae could be compared on a force-per-unit-area basis.

Since there is evidence that age and state of preservation have a significant influence on strength, not all values in the literature are of interest and some have been omitted from discussion on that basis.

There is a lack of data under dynamic conditions in general. Perey (1957) dropped weights from known heights to break specimens consisting of two vertebrae and one disc in an endeavor to measure dynamic strength. Although a peak force is tabulated, no evidence is given that the actual waveform was measured. In its absence, the load must be treated as a momentum change, rather than acceleration. The specimens came from persons older than the pilot population, making the values less applicable to the present study.

No measurements of dynamic stiffness were found.

The only measurement of stiffness or strength, either static or dynamic, under bending conditions was that of Brown, Hansen, and Yorra (1957) who measured the bending moment at a given angle of a disc to which a fixed axial load was applied.

Thus, the literature lacks data for many cases of interest, especially those of bending and dynamic conditions. The experiments described in the following sections of this report provide new data on dynamic stiffness and strength, and in so doing, resolve the question of the relative stiffness of the centrum and disc. Bending effects have not been considered in the current work.

EXPERIMENTAL OBJECTIVES

The experiments were designed to answer three questions:
1. Does the stiffness of the spine change with rate of deformation?
2. How does the stiffness of the centrum compare with that of the disc?
3. Does breaking strength change with rate of deformation?

To accomplish this, groups of human vertebrae were tested in axial compression. Axial force and axial deflection of both disc and centrum were measured at several rates of deformation, and then the vertebrae were fractured.

MATERIALS AND METHODS

Specimens

Tests were made on fresh pork and human vertebrae. Pork vertebrae were used to develop techniques. When the experimenters had become proficient and the equipment proven, then human vertebrae were tested. These vertebrae consisted of the groups listed in Table 1, taken at autopsy from two individuals with permission of their next-of-kin, and stored in a freezer at -20°C for 6 months (J. T. Z.) and 3 months (R. R. W.) until tested. To check for the possibility of an unobserved thaw during this long period, a rubber band was stretched around an ice cube and stored with the specimens.

The specimen from J. T. Z. consisted of a column of vertebral centra separated from the posterior processes by saw cuts through the pedicles. A saw cut across the centrum of T11(11th thoracic) had separated the column into two parts, one of which contained T7-T10, the other T12-L5 (5th Lumbar). The T7-T10 specimen included the ends of T6 and T11, and the T12-L5 specimen included the ends of T11 and the sacrum.

The specimen from R. R. W. consisted of a column of four vertebrae: T11, T12, L1, and L2, complete with transverse and spinous processes and with ligaments intact, from anterior longitudinal to supraspinal. The ends of T10 and L3 were included in the specimen.

Table 1 contains values for dimensions and mass of the vertebrae and for the disc. A search of the literature has been successful in locating previous values only for the dimensions of the vertebrae. Those from papers by Cyriax (1920) and Anderson (1883) are tabulated for comparison in Table 2.

Instrumentation

The specimens were placed in the hydraulic testing machine described in Appendix 1, and instrumented with electrical input transducers for force, deflection and noise. Output signals of the transducers were conditioned and recorded. Figure 1 gives a view of the experimental arrangement. Characteristics of the transducers and recording system will be discussed next. Following that, the experimental procedure will be taken up.

The force transducer was a 5000 lb_f production unit with a resonant frequency of 5 kHz and a stiffness of 0.0005 inch per 1000 lb. Its electrical output resulted from the resistance change of two semiconductor strain gages

TABLE 1. - MEASUREMENTS OF VERTEBRAE OBTAINED FROM RRW AND JTZ

		RRW				JTZ										
Complete Vertebra		T11	T12	L1	L2	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5
Overall Dimensions	mm															
1. A - P		77	78	84	88					complete vertebrae not available						
2. Transv.		60*	46	65	58*											
3. Mass	gm	56.9*	56.1*	73.9*	72.5*											
Centrum																
Dimensions	mm															
4. AP Sup.		---	36	---	38	---	33	30	30	30	---	30	31	---	33	35
5. Inf.		34	---	37	---	30	31	30	---	32	29	30	32	32	35	---
6. Transv. Sup.		---	46	---	48	---	35	34	35	37	---	47	48	---	54	56
7. Inf.		46	---	50	---	36	35	37	---	44	46	50	53	54	56	---
8. Height Ant.		24*	25*	26*	23*	17.8*	17.2*	22	21*	---	24	---	26	27*	30	15*
9. Post.		24*	27*	26*	26*	15.5*	22.5	24	19*	---	---	---	28	28*	29	22*
10. Area Sup., cm^2		---	14.3	---	16.6	---	10.9	9.3	9.5	9.9	---	11.8*	12.8*	---	16.0	---
11. Inf.		13.8	---	16.9	---	8.8	9.8	9.1	---	11.5	11.3*	12.1*	---	15.1	15.5*	---
12. Mass	gm					14.7*	21.0	25.8	23.1*	28.4*	27.6*	27.0	33.2*	41.2*	47.2	30.9*
Disc																
Dimensions	mm															
13. AP Sup.		33.0	---	---	40.0	31.5	31.0	31.0	31.0	31.0	30.0	31.0	33.0	32.0	35.0	35.5
14. Inf.		---	36.5	40.0	40.0	31.5	29.5	32.0	31.0	33.0	32.0	31.0	31.5	---	36.0	---
15. Transv. Sup.		41.5	---	---	50.5	34.0	36.0	36.0	35.0	39.0	45.0	48.5	51.0	49.0	57.5	57.5
16. Inf.		---	46.5	50.5	51.5	35.0	36.0	36.5	36.0	47.0	49.5	50.0	51.0	---	59.5	---
17. Height Ant.																
18. Post.																
19. Area Sup.	cm^2	11.9	---	---	18.0	7.9	8.8	9.7	9.1	10.6	12.2	11.7	13.7	15.2	16.9	16.6
20. Inf.		---	14.1	17.5	18.6	9.0	8.8	9.3	10.5	13.2	12.3	13.3	14.8	---	17.5	---
21. Mass	gm	11.9	---	16.0		3.7	3.6	4.5	---	---	8.7	11.6	---	18.4	19.2	

Values in this table were measured from photographs taken of the endmost discs before test, and from photographs, radiographs or directly from the vertebrae following dissection after test. Certain of the values are known to be low; these are marked with asterisks * and generally result from the loss of mass and height when the endmost vertebrae were squared by rasping the end plate before test.

TABLE 2. - MEASUREMENTS OF VERTEBRAE FROM LITERATURE

	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5
Overall Dimensions Vertebrae (Cyriax)											
Anterior-Posterior, Mean	69.6	70.0	71.4	70.6	71.0	73.2	73.2	81.9	83.5	82.3	76.5
Range	(58-80)	(60-80)	(60-84)	(58-81)	(58-86)	(61-89)	(61-89)	(69-92)	(70-95)	(69-94)	(61-96)
Transverse, Mean	64.4	62.5	64.2	58.5	53.2	47.9	47.9	80.2	89.1	83.6	86.0
Range	(54-77)	(52-70)	(52-71)	(49-67)	(44-66)	(38-63)	(58-88)	(64-93)	(69-108)	(63-102)	(68-108)
Dimensions of Centrum (Anderson)											
Anterior-Posterior, **Mean**	26.8	28.2	29.4	29.4	29.8	30.0	29.9	31.9	36.8	33.8	36.5
Range	(25. 31)	(25-33)	(26-35)	(27-37)	(27-37)	(25-35)	(25-37)	(26-43)	(29-44)	(27-43)	(29-44)
Transverse, **Mean**	28.8	30.1	31.9	34.1	36.5	40.5	42.2	44.0	47.7	48.3	52.7
Range	(26-32)	(27-33)	(28-34)	(30-40)	(32-45)	(33-45)	(37-51)	(40-53)	(43-57)	(43-57)	(43-63)
Anterior Height, Mean	18.5	18.9	19.7	21.0	21.9	23.6	24.6	25.9	26.7	26.1	27.2
Posterior Height, Mean	20.6	21.6	21.9	22.9	24.9	25.4	26.5	27.4	27.0	26.0	22.2

This presents data taken from the literature for comparison with some of the measurements in Table 1. Overall dimensions were measured by Cyriax in 1920 on between 32 and 113 skeletons and dry vertebrae for each average value tabulated. Centrum dimensions, including height, were measured by Anderson (Demonstrator of Anatomy at Queen's College, Belfast) in 1883 on 53 vertebral columns of adults.

Although he did not state it explicitly, his specimens presumably were fresh or embalmed. Cyriax also measured the centrum dimensions of his dry specimens, obtaining consistently lower values that are not repeated here.

connected with two fixed resistors in a four-arm, 120 ohm bridge. Nominal output was 31.05 millivolts per 1000 lbs. at the 5 v excitation used.

The force channel of the recording system was calibrated directly from force input to oscillographic output by means of the testing machine and a portable electronic load cell and null-balance indicator operated by an independent testing laboratory. The load cell's calibration by its manufacturer was traceable to the National Bureau of Standards.

The displacement transducers were flat cantilever beams of 0.017 inch hardened stainless steel strip 0.25 inches wide extending 0.75 inches beyond the cantilever support. To each beam were cemented two 120 ohm semiconductor strain gages. Together with two fixed resistors inside the supporting tube, these formed a four-arm, 120 ohm bridge.

Linearity of electrical output as a function of deflection of the free end of the cantilever was measured using a millimeter micrometer head in the rigid fixture shown in Figure 2. The resulting voltage output (5 volt excitation) as a function of deflection (Figure 3) is linear within 2% of full scale (3mm). Conditions for electrically realizing the exact linear analytical relationship between deflection of the free end of a cantilever and strain of the surface at a given point were not met because the active length of the gages (0.25 inch) was not small in comparison with the length of the beam (0.75 inch).

Natural frequency (910 Hz) and damping (0.04) of the short stiff beam in air are shown by the oscillographic recording inset in Figure 3.

The noise transducer was a ceramic microphone cartridge (its active element a beam of piezoelectric material) coupled by a piano wire whisker to an exposed bony surface of the centrum. Noise originating within it due to fracture of the bone was conducted to the transducer, and the resulting electrical signal was amplified and recorded on one channel of the oscillogram in an attempt to pinpoint the exact time and force at which crushing occurred.

The force and displacement transducers were supplied with a 3 kHz, 5 volt excitation. Their output was amplified by a 0.50 kHz carrier amplifier, and that of the piezoelectric noise transducer was amplified by a 2.00 kHz instrumentation amplifier. The output of these amplifiers drove the 1 kHz galvanometers of a 36 channel, closed magazine, oscillograph.

PROCEDURE

In general, the specimen was removed from the deep freeze and prepared (during which time it warmed to room temperature). The preparation was then placed in the testing machine and instrumented, as shown in Figure 4. Loads were then applied in several trials at various rates to reversible levels and finally to fracture.

Preparation

The discs at each end of the specimen were sliced across the middle and photographed against a centimeter scale or grid co-planar with the disc surface. The specimen was then placed in a fixture. On the first two tests, ends were squared with a coarse "vixen" file (curved tooth rasp). The exposed spongiosa was capped with three-minute dental impression plaster between parallel steel plates. The discs were left intact on later specimens.

In order to record separately the deflection of the centrum and the disc, sharpened steel pins of piano wire (1 mm dia) were pressed into the edges of the centrum at one or more points in the circumference adjacent to each endplate. The end of a displacement transducer contacted each pin and moved with it to record its motion as loading progressed.

In the case of the two-vertebra preparations, the endplates above and below the disc were both instrumented. In the three and four vertebra preparations, one centrum and one disc were selected for study. The centrum was instrumented at both its endplates, and the adjacent end of a neighboring centrum was instrumented to measure the compression of the intervening disc.

Loading

Three valve settings were used, which resulted in ram speeds under loads of 0.1, 0.7 and 4.0 mm/sec.

The valve produced a constant flow of hydraulic oil, and the resulting ram speed was constant within 20% except initially, when the compressibility of air within the piston had most effect.

Data Reduction

Each test resulted in an oscillogram of the variables as a function of time. Figure 5 provides an example. Each oscillogram was read at ten points. The values were tabulated and force then plotted as a function of deflection, either of the whole preparation or of the parts of interest, such as centrum and disc.

RESULTS

A linear force-deflection relationship has been found to exist under certain conditions of axial loading. Non-Hookean behavior is limited to loads near ultimate and to low rates of loading.

Figures 6 and 7 show the results of measurement of relative deflection of disc and centrum from anterior and lateral surfaces. The results are similar and indicate at least three times greater stiffness for the centrum, when compared with the disc.

With increasing deflection rates, the stiffness increases over that found in static tests. Figure 8 shows the force-deflection characteristics of L1-L2 with intervertebral disc intact for 0.1, 0.7 and 4 mm/sec. rates of deflection and is plotted with data from the literature.

Radiographs and photographs of vertebrae tested are shown in Figures 9-12. An actual ejection-sustained fracture of L1 is illustrated in Figures 13 and 14.

Table 3 relates level of fracture and fracture loads to vertebrae tested.

TABLE 3. - FRACTURE LOADS

Source	Preparation	Ram Speed mm/sec.	Vertebra Fractured	Fracture Load kp
JTZ	T7 - T10	3.5	T8	536
(Age 47)	T12 - L2		L1	
	L3 - L5	0.1	L5	270
RRW	T11 - T12	4.2	T12	974
(Age 40)	L1 - L2	4.2	L1	1125

Figure 15 compares breaking strengths of the bones tested with those available from the literature. The number of bones tested thus far is too small to draw conclusions at this point.

CONCLUSIONS

Measurements of the dynamic strength of isolated vertebrae from two individuals has been accomplished. A linear force-deflection relationship (Hookean) was found to exist under axial loading almost to the point of fracture. Thus, the non-Hookean portion is quite brief.

That the higher rate of loading results in a stiffer vertebra under dynamic stress was confirmed for the two specimens tested. This would correspond to a statement that a higher frequency input environment would result in greater stiffness of the vertebral bones. Specimen numbers were insufficient to support an hypothesis of greater breaking strength in a higher frequency acceleration environment.

Our experiments have shown that the centrum of a vertebra is stiffer (up to the point of fracture) than the disc.

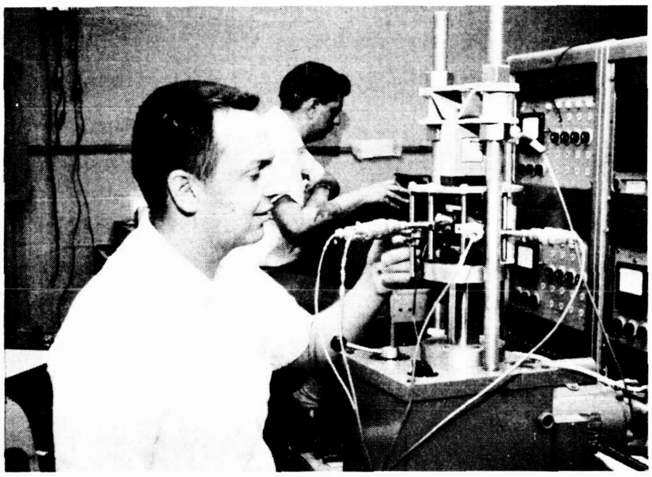

Figure 1. Recording System Prepared for Test

By moving the active element of one of the transducers grouped around the specimen, the testing machine operator generates an electrical input that is conducted by cable to one channel of the three carrier amplifiers in the rack at right. Output of the amplifier is conducted by a second cable to the oscillograph at the rear, whose operator observes a visible signal that the recording channel is operative.

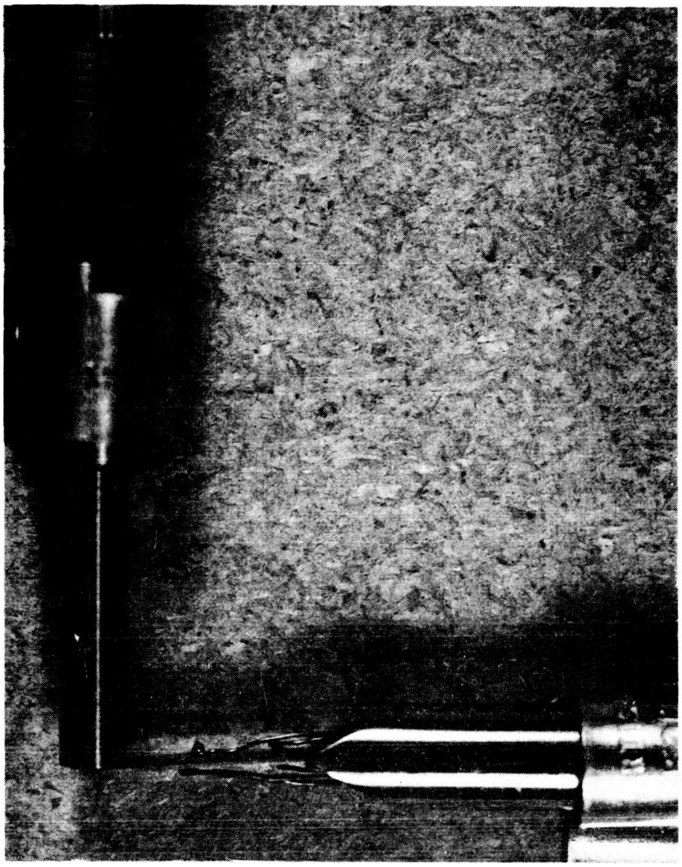

Figure 2. Calibration of a Displacement Transducer

The displacement transducer (horizontal) was clamped in a fixture at right angles to the barrel of a millimeter micrometer (vertical) with its blade overlapping the micrometer 1 mm or less. By turning the micrometer, chosen displacements could be introduced accurately for calibration.

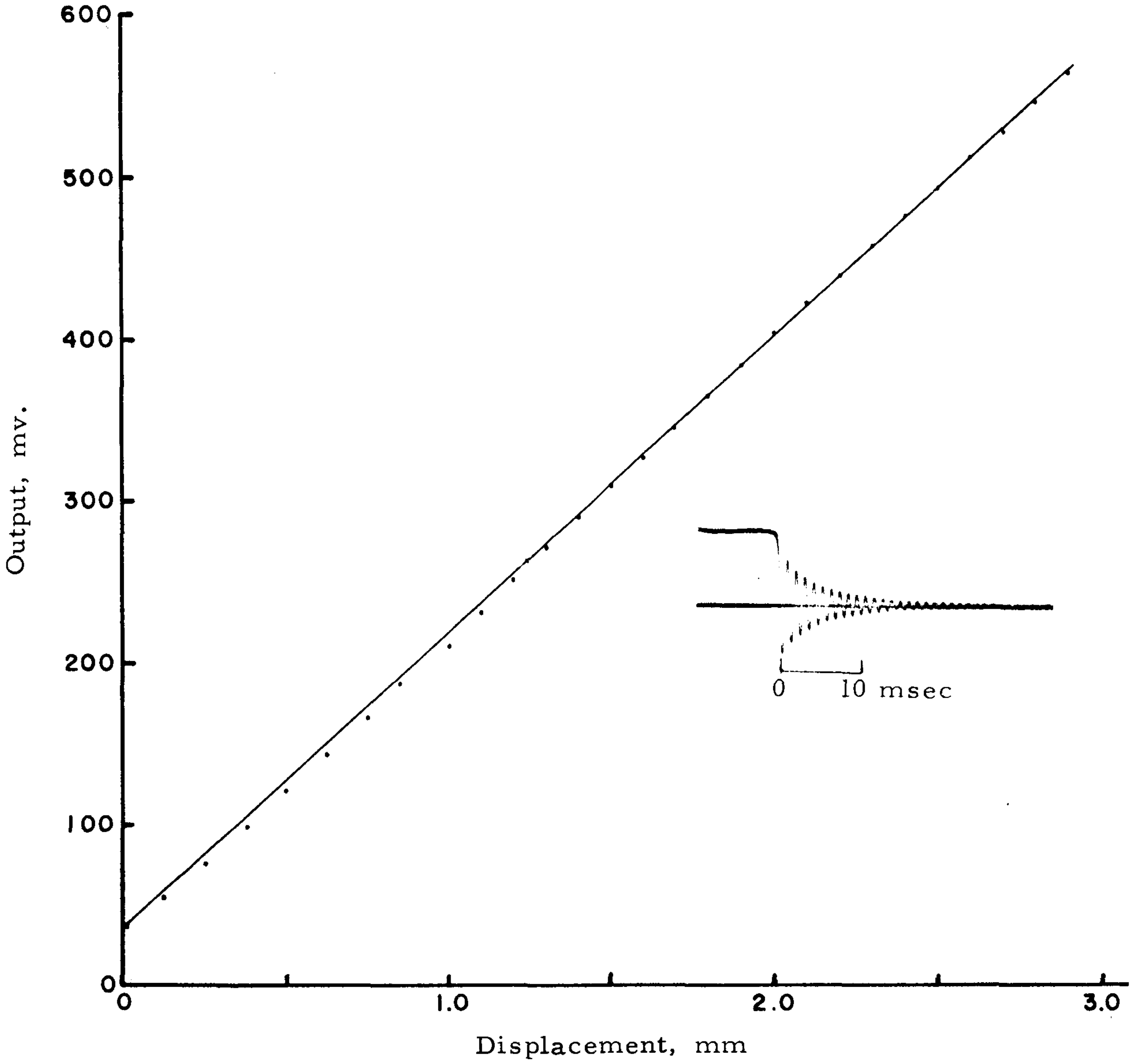

Figure 3. Displacement Transducer Characteristics

Displacement transducer output under an excitation of 5 v.d.c. is plotted vs. lateral displacement of the flat springblade. Voltage was read with a digital, 0.1% voltmeter. A resistive unbalance is responsible for the output at zero deflection.

The high natural frequency of the transducer is shown in the inset oscillogram generated when the blade was released from an initial 1 mm deflection.

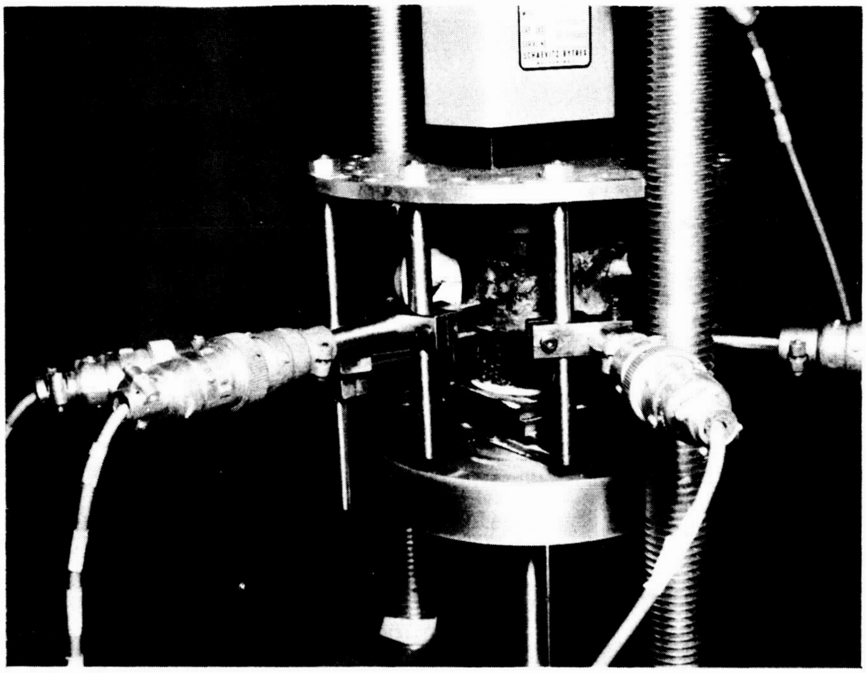

Figure 4. Close-up of Specimen in Testing Machine

A two-vertebra preparation of T11, T12 of RRW, plaster capped, is resting on steel spacer plates to prevent interference between the inferior articular processes of T12 and the hydraulic ram below. The upper surface of T11 is in contact with an extension of the load cell, to which is bolted a 1/4 inch thick circular plate, which supports the rods and clamps holding the noise and displacement transducers. Since little force is applied to the transducers, their positions remain accurately referenced to the load cell, independent of strains under load in the main reaction members, the two threaded rods, and the crosshead out of picture above the load cell.

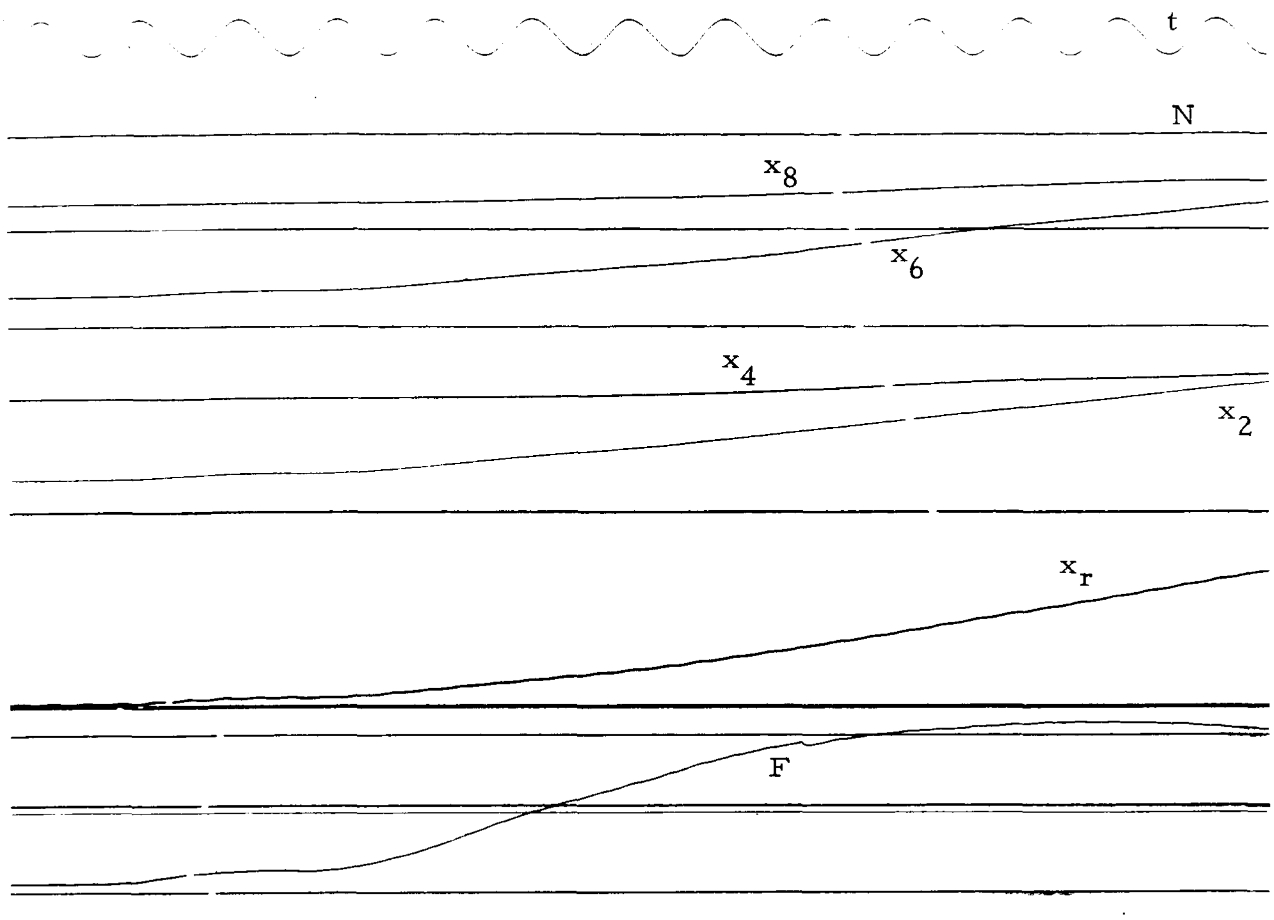

Figure 5. Multichannel Oscillogram of Fracture

This is an exact, 2:1 reduction of 1.3 seconds of original record during which the force applied to L1 and L2 of RRW went from zero to a peak of 1125 kp, fracturing L1. The active traces are keyed by letter to the following table; the remaining horizontal traces served as references for measurement.

t	10 Hz timing signal
N	Noise (inactive)
x_8 x_4	Deflection of pins in the lateral and anterior margins of the inferior end plate of L1.
x_6 x_2	Deflection of pins in the lateral and anterior margins of the superior end plate of L2.
x_r	Displacement of the ram
F	Force measured by the force transducer

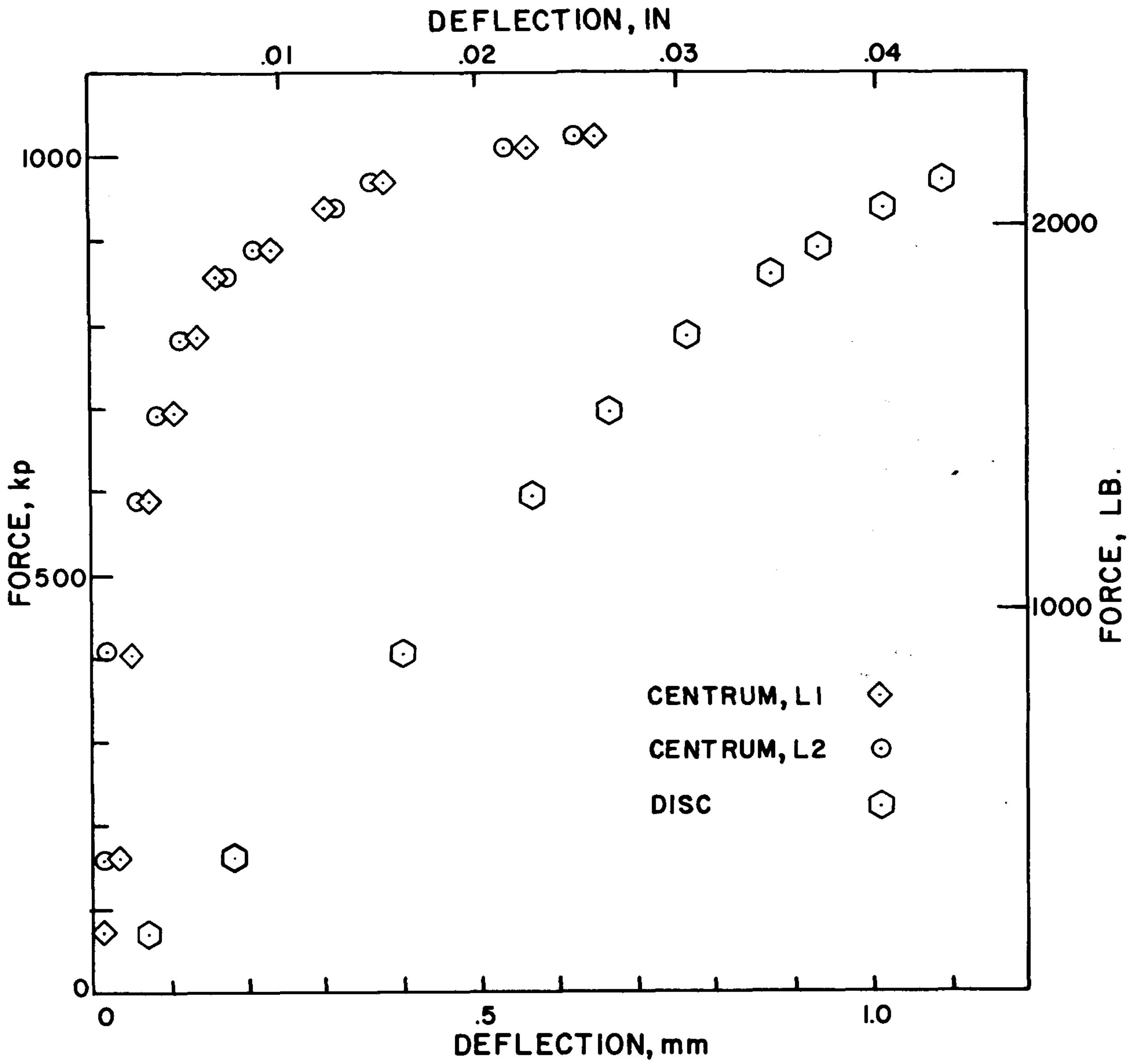

Figure 6. - Deflection of Centrum and Disc Measured on the Anterior Surface

Two transducers registered the motion of pins pressed into the edges of the end plates of L1 and L2 of RRW; a third registered the motion of the ram, and with it that of the lower surface of L2. The oscillogram was read at a number of points in time. By subtraction, the net deflection of the centrum of L2, the disc, and the centrum of L1 were calculated and plotted.

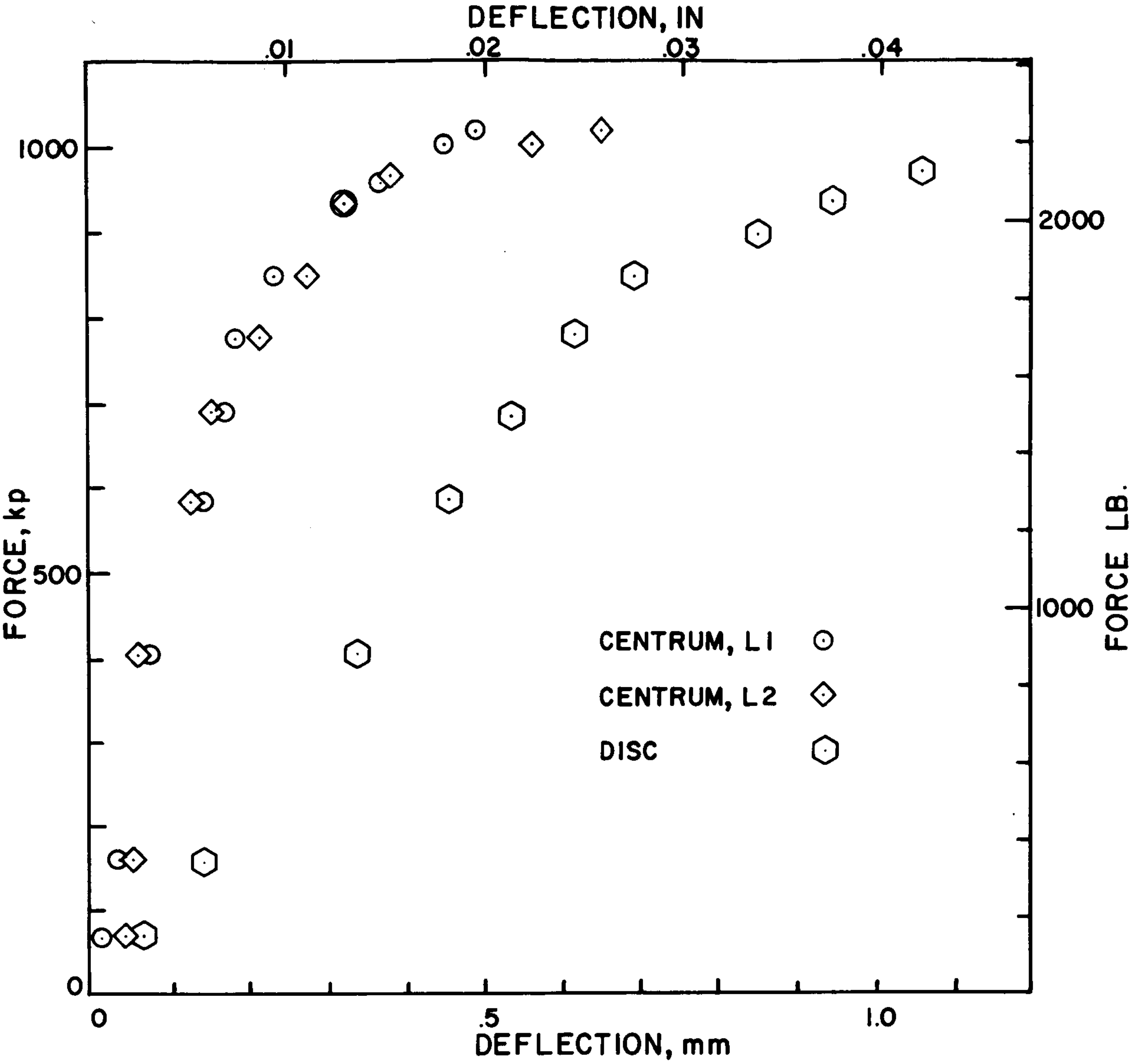

Figure 7. - Deflection of Centrum and Disc Measured on the Lateral Surface

The method of calculating the values follows that of Figure 6. Comparing the initial slopes of the two plots shows the disc to be stiffer laterally (1, 300 vs 1, 000 kp/mm) than anteriorly, and the centra to be stiffer anteriorly than laterally (7, 700 vs 4, 300 kp/mm). More important, the centrum stiffness in both cases is many times that of the disc.

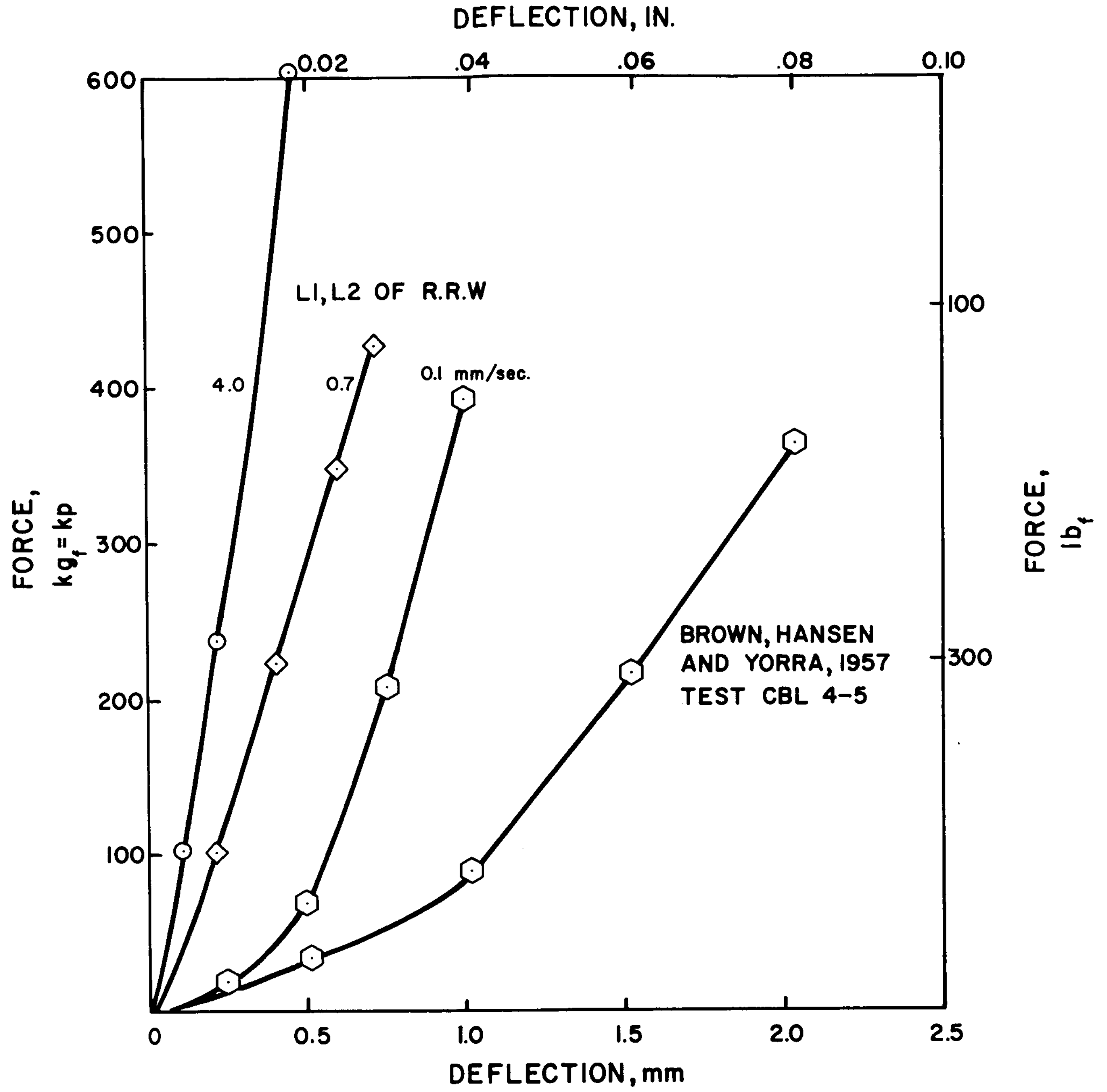

Figure 8. - Effect of Rate of Deflection upon Stiffness

Force is plotted against the overall deflection of a preparation of two vertebrae and one disc. Three curves were measured at increasing rates of deflection on L1 - L2 of RRW. The fourth is from the literature and was measured at a rate of deflection near zero.

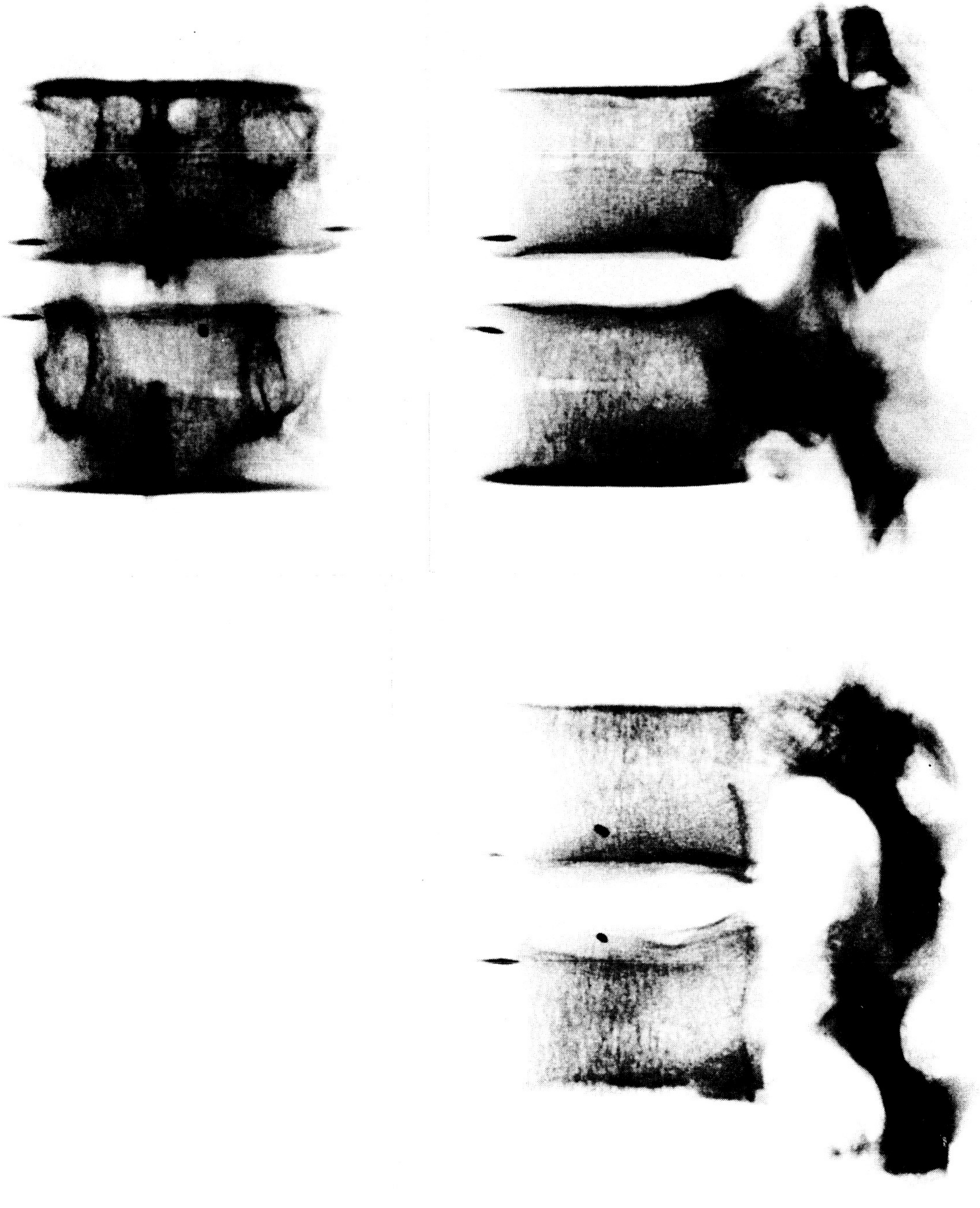

Figure 9. - Radiographs of T11-T12, and L1-L2 of RRW

Radiographs of two-vertebra preparations from RRW. The anterior-posterior (A-P) and lateral views (upper) are T11, T12; the lateral view (lower) is of L1, L2, both after test. Steel pins in the margins of the end-plates visible in both were used to contact the displacement transducers.

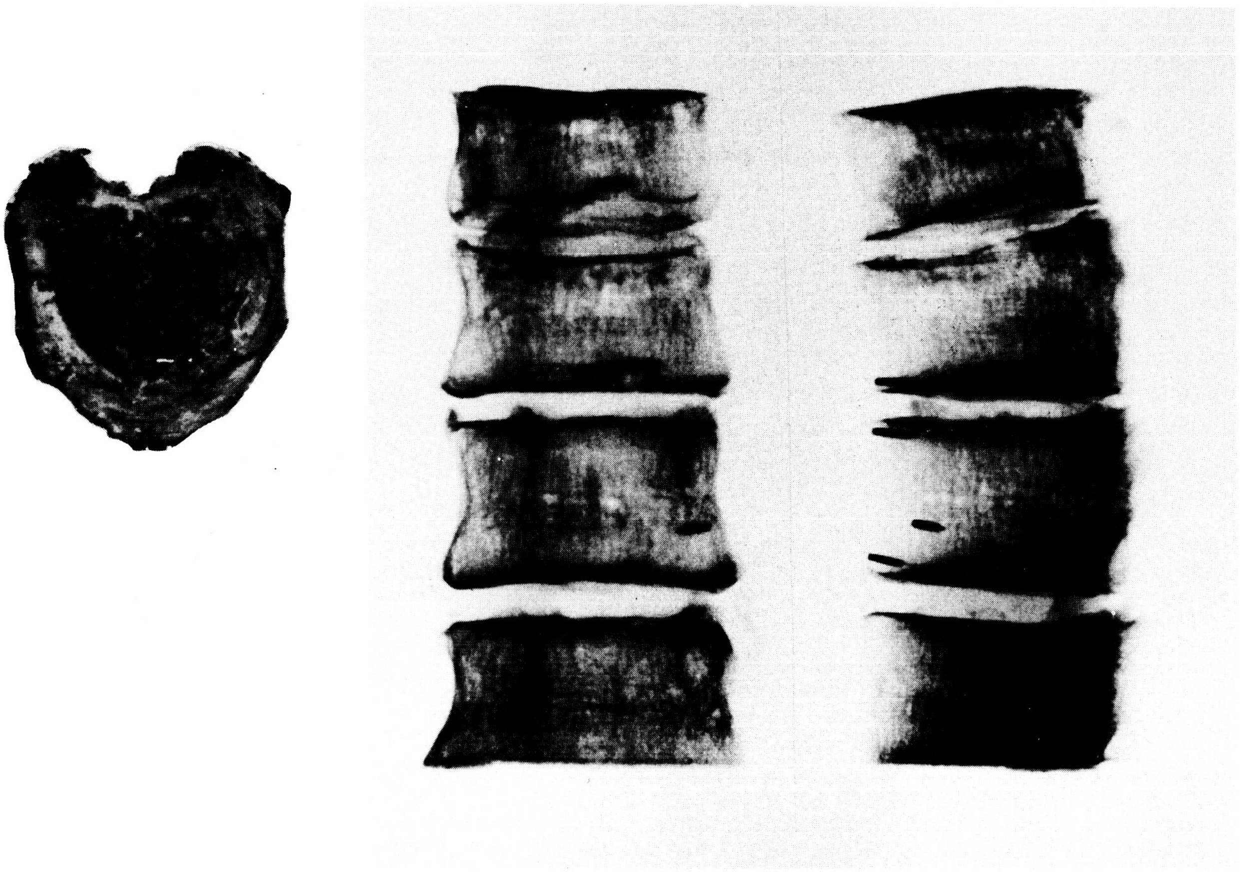

Figure 10. - Photograph and Radiographs of T7-T10 of JTZ

The A-P and lateral views above were taken after tests. A compression fracture with anterior wedging is visible in the lateral view. The photograph of the superior surface of T8 shows two transverse cracks. The Schmorl's nodes visible in the radiograph of the inferior surface of T7 and T8 were substantiated by dissection.

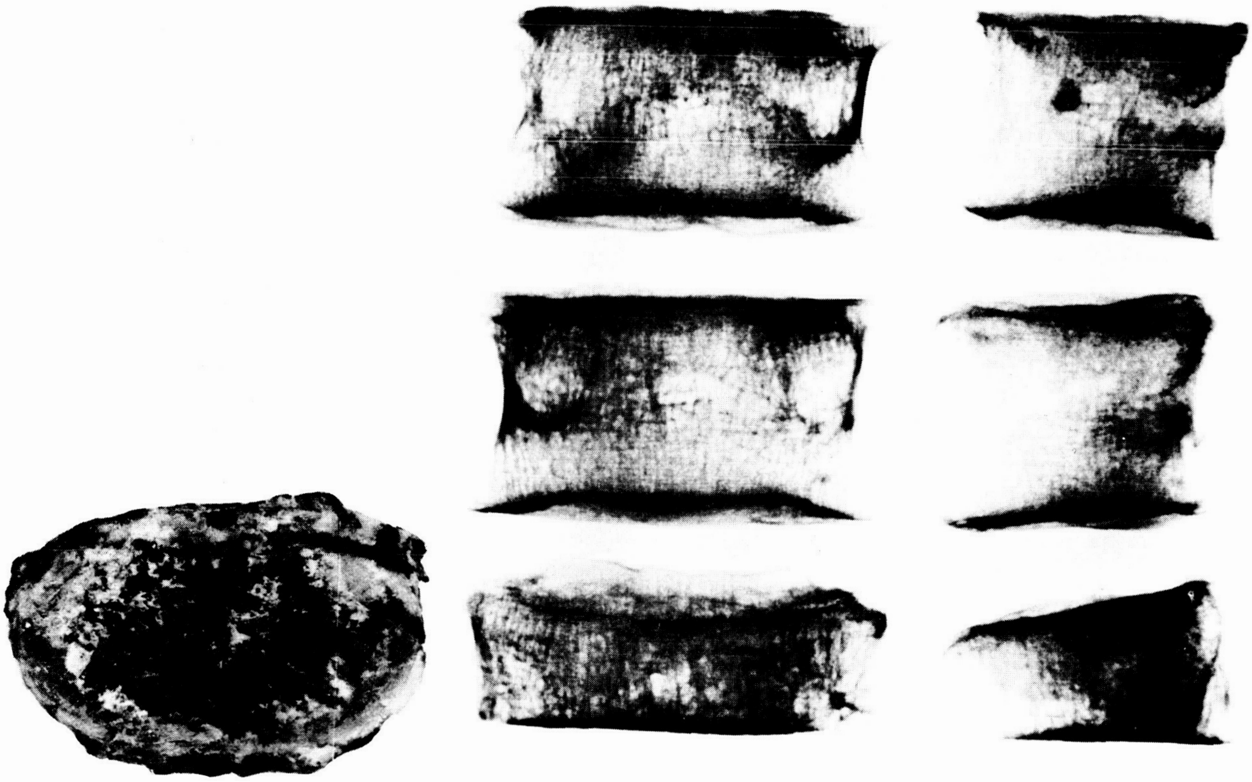

Figure 11. - Photograph and Radiographs of L3-L5 of JTZ

The A-P and lateral views were taken after tests in which fracture occurred at an unusually low force level. The photograph of the superior surface of L5 shows two saw cuts, with a crack proceeding away from the lower, that were discovered upon dissection and which may explain why fracture occurred at such a low level.

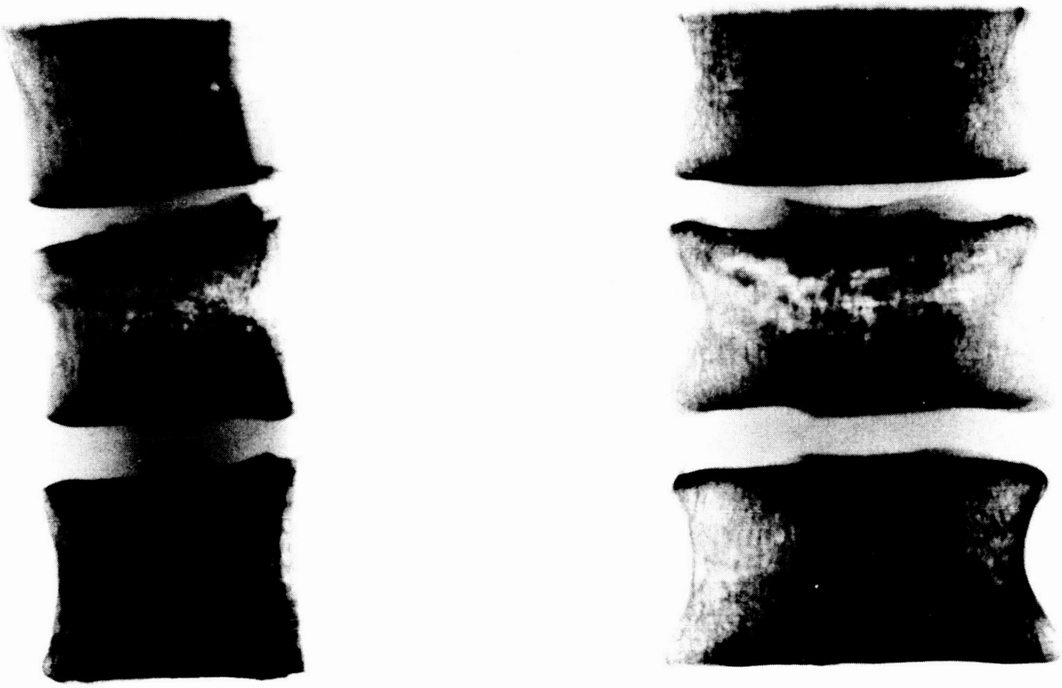

Figure 12. - Radiographs of T12-L2 of JTZ

Figure 13. - Ejection Fracture of L1 of JTZ - Disc

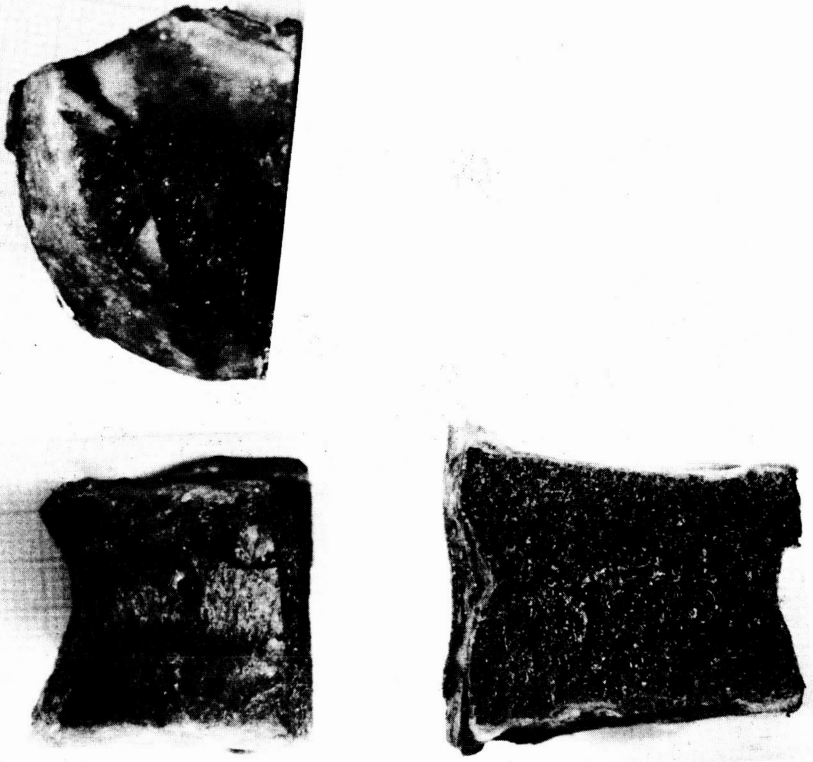

Figure 14. - Ejection Fracture of L1 of JTZ - Centrum

Superior and anterior views of the left half of the centrum, although apparently scattered, are oriented (top and left) in orthographic projection to show the relationship of the cracked endplate to the fractured anterior wall of the centrum. (The inferior endplate was not cracked.)

The sawed section (right) is of the mating surface; hence, its orientation is reversed. (No photograph of its mirror image on the left half of the centrum was taken.)

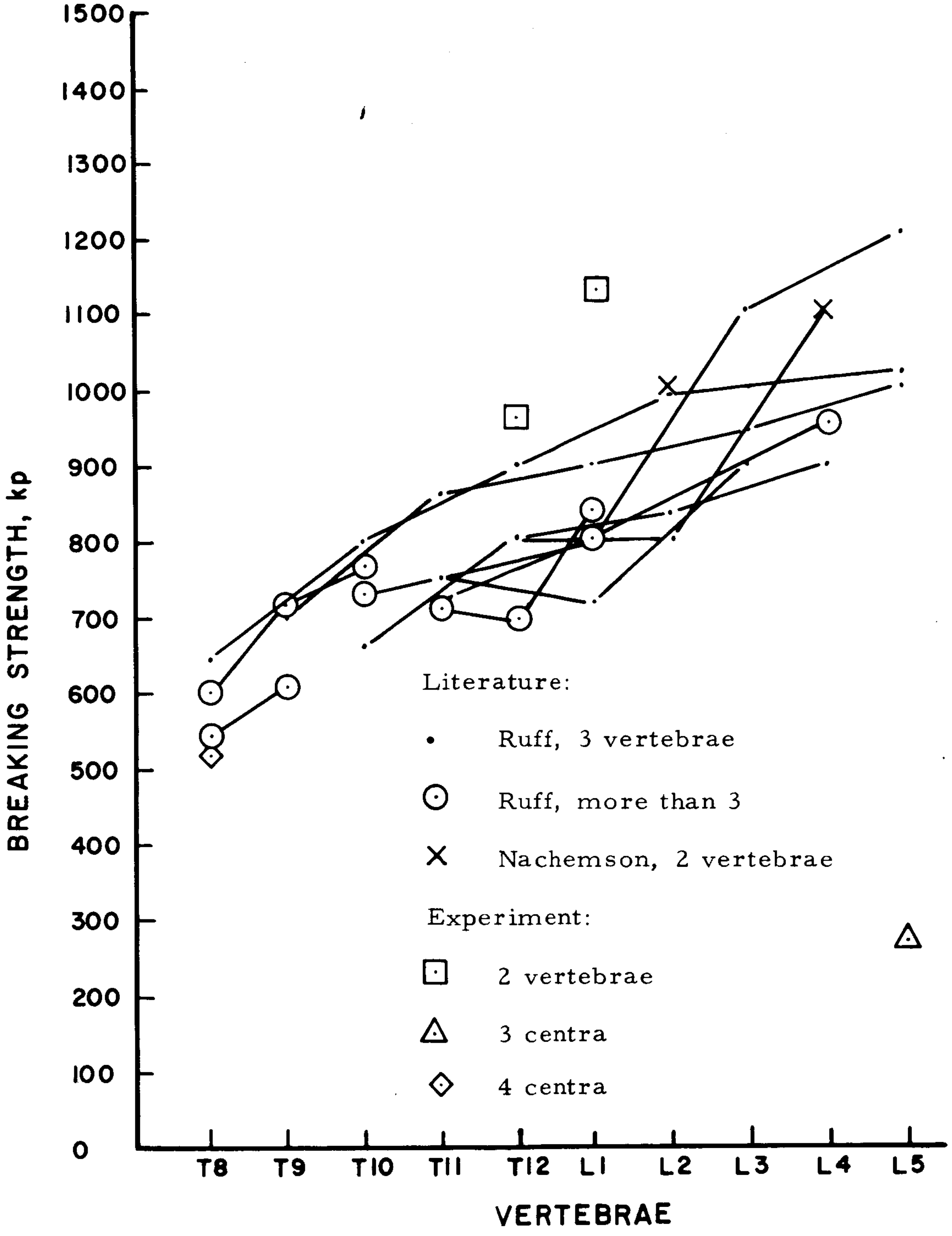

Figure 15. - Comparison of Experimental Results with Values from the Literature

LIST OF EQUIPMENT

Model LPT testing machine, modified to 3000 lb. capacity in compression. (Detroit Testing Machine Co., Detroit, Michigan)

Model JP-5000 force transducer. Serial A-5666. (Schaevitz-Bytrex, Waltham, Massachusetts)

Model DB-112, bonded 120 ohm semiconductor strain gages. (Kulite Semiconductor Products, Ridgefield, New Jersey)

Model 1-118, 500 Hz carrier amplifier, modified with a 1.5 megohm series resistor on the input. Serials 12009, 12018, 12025, (Consolidated Electrodynamics Corporation, Pasadena, California)

Model MC 559-2 microphone cartridge. Disassembled and modified. (The Astatic Corporation, Conneaut, Ohio)

Model 111 BF, DC-2 kHz, amplifier. Serial 6672. (Kin Tel Division, Cohu Electronics, San Diego, California)

Model 840 Frequency-time Counter. (Potter Instrument Co., Plainview, New York)

Model 5-119, 36 channel oscillograph, Serial 367DS4 with Model 7-323 (f_n = 1kc) galvanometers. (Consolidated Electrodynamics Corporation, Pasadena, California)

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