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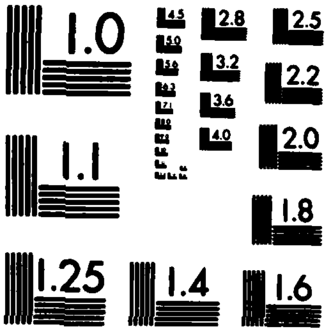

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DIGEST

In 1977, the American Dental Association published Specification No. 32 for orthodontic wires not containing precious metals. A static-flexural-test portion was included within the Specification toward determination of elastic moduli and yield strengths of orthodontic wires. The flexure test has proved inadequate for the newer, more flexible wires, notable when specimen failures occurred before elastic limits were reached.

The purpose of this study was to critique an alternative flexure test that could replace the format used in Specification No. 32. The test incorporated transverse activation, split anchorage, and bracket-simulating supports. The new format was designed to be more clincially oriented; sought were two elastic structural properties: transverse stiffness and elastic-limit range. Wires of orthodontic stainless steel and two titanium alloys were tested and the effects of cross-sectional shape and size, test-span length, and support width were included and controlled to determine their influence on the two dependent variables. Stiffness and elastic-range values for each of the 288 test specimens were determined analytically from the force-deflection data and evaluated statistically through analysis-of-variance procedures.

The results ranked as suggested by engineering beam theory, but stiffness and range ratios differed from theoretical expectations. Deviations were due primarily to two factors: 1) Theory does not account for the presence of frictional forces at the support sites. 2) The formulas generally used for stiffness and range are based on small-deflection theory. The more flexible wires experienced "large deflections" prior to reaching their elastic limits. Correcting the theory to account for sizable deflections decreases stiffnesses and increases elastic ranges compared to values predicted by traditional beam equations.

The alternative test format is an improvement to Specification No. 32. Most importantly, elastic-limit ranges can be determined for the lighter titanium wires with relatively few buckling failures.

Additional keyword: bending.

STRUCTURAL PROPERTIES OF SINGLE-STRAND ORTHODONTIC WIRES FROM A PROPOSED ALTERNATIVE STANDARD FLEXURE TEST

Marion L. Messersmith, D.D.S.

A Thesis Presented to the Faculty of the Graduate
School of Saint Louis University in Partial
Fulfillment of the Requirements for the
Degree of Master of Science in
Dentistry
1984

COMMITTEE IN CHARGE OF CANDIDACY

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Clinical Professor Peter G. Sotiropoulos

DEDICATION

To my wife Mary, your love and constant support made this thesis possible. To my son, Peter, and my parents Leonard and Pauline, thank you for sustaining me in this effort.

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CHAPTER I

INTRODUCTION

The relatively recent introduction of titanium-alloy and multistrand-steel wires has offered a new adjunct to the orthodontist who wishes to "optimize" force magnitudes and simultaneously allow full bracket engagement of initial leveling wires without resorting to looped-wire configurations. The quantification of several characteristic elastic properties of the "newer" wires has been delayed due to inadequacies within the existing cantilever test format of A.D.A. Specification No. 32. The clinician who would select wires using recent published results has been given data based on theory or a combination of experimentally and theoretically established values for a limited sample of wires. Compounding the confusion were studies that contained values for elastic moduli and yield strength which require an understanding of engineering formulas to interpret and transform to the clinical arena. Moreover, reaching the elastic limit in the testing of lighter wires has been problematic.

With these deficiencies present, an alternative

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flexure test format was apparently needed. Moreover, rather than determine mechanical properties of elastic moduli and yield strength as in the present Specification, structural stiffnesses and elastic ranges seem more clinically appropriate. Stiffness, when multiplied by the activating deflection, gives the initial force magnitude exerted by the appliance as well as the rate of force decay as gradual deactivation occurs with tooth movement at the activation site. Elastic range is the maximum amount of activating deflection tolerable by the appliance before permanent distortion occurs upon unloading.

A suitable alternative test would feature transverse loading at the midspan of a symmetric split-anchorage wire beam; the distance between one support and midspan represents an interbracket distance. Replacing the single knife-edge support of Specification No. 32 (which provided no rotational constraint and resulted in excessive deformations) with bracket-like supports would lower range. The influence of support width on elastic properties has not been previously reported in the literature.

Accordingly, the purpose of this study was to evaluate a clinically-oriented bending-test design by quantifying the two elastic properties, transverse stiffness and elastic range, as influenced by cross-sectional shape and size, span length, and support width for a sizable sample of the newer single-strand and conventional steel wires. The results of this study are intended to demonstrate the viability of a new test format and provide the clinician with arch-wire comparisons more directly transferable to clinical application.

CHAPTER II

REVIEW OF THE LITERATURE

Optimum Forces

Interest in the use of lighter active force systems to optimize the rate of tooth movement has increased in recent years among both clinicians and researchers. Storey and Smith (1952) proposed an optimum force range of 150-200 grams for cuspid retraction. They further termed the force that resulted in the maximum rate of bone resorption the "optimum force". Increasing the force beyond this "optimum" level caused loss of anchorage with resultant movement of the anchor units. Begg (1961) put this differential-force finding into clinical use with the introduction of his "light-wire" technique utilizing small round wires and light elastic forces.

Reitan (1957) found in a histological study that initial tooth movement required time for the cells on the tension side to proliferate and form osteoid. This time period varied from one or two days for children and up to eight days for adults. Heavy initial forces offered no advantages and, in fact, resulted in cell-free hyalinized areas which were associated with a retarded rate of tooth movement. Reitan (1957) suggested an initial force of 25 grams in adults and about 40 grams in children. In a clinical study, Burstone and Groves (1960) found in children that retraction of anterior teeth by simple tipping was optimal when forces of 50-75 grams per quadrant were applied. Increasing the force magnitude did not increase the rate of tooth movement and, in fact, was associated with patient discomfort.

Burstone (1981) noted that the force exerted by a simple alignment arch-wire was not constant as the teeth moved. Four ranges of force magnitude could be differentiated, varying from a heavy range when the wire was initially tied to the malposed tooth, to optimal, suboptimal, and threshold ranges as tooth movement occurred.

The optimum force, then, is "that force which produces a maximal desirable biologic response with minimal tissue damage, resulting in rapid tooth movement with little or no clinical discomfort" (Nikolai, 1975). Although there have been studies that are in disagreement with the optimum-force theory (Hixon, Aasen, Arango, Clark, Klosterman, Miller, and Odom, 1970; Boester and Johnston, 1974), the trend today is toward use of materials and arch-wire configurations that deliver lighter forces than those of conventional single-strand, stainless-steel wires.

Orthodontic Arch-wire History

The earliest orthodontic arch wires were made of gold alloys of 55-60% gold, 11-18% copper, 5-10% platinum, 10-25% silver, 5-10% palladium, and 1-2% nickel. This material has a modulus of elasticity of approximately 16,000,000 lb./in.^{2} and a yield strength from 50,000 to 160,000 lb./in.^{2} (Burstone and Goldberg, 1980). Although gold arch wires have good formability and lighter force capability than corresponding stainless steel wires, their use declined in the late 1930's and 1940's due to relatively high cost and the increased availability of stainless-steel arch wires.

Orthodontic stainless-steel arch wires are composed of approximately 74% iron, 18% chromium, 8% nickel, and 0.2% carbon. The modulus of elasticity of stainless-steel is approximately 29,000,000 lb./in.^{2} and the yield strength varies from 50,000 to 250,000 lb./in.^{2} (Burstone and Goldberg, 1980). Clinicians using stainless steel typically progress through a series of light to heavier leveling arches. Burstone (1981) termed this treatment procedure "variable-cross-section" orthodontics and noted that the clinician was varying the force by changing stiffnesses or load-deflection rates simply through wire size.

In the late 60's wires from a chrome-cobalt alloy used in watch springs were introduced for orthodontic use. Elgiloy (Rocky Mountain Orthodontics, Denver, CO) is composed of 40% cobalt, 20% chromium, 15% nickel, 7% molybdenum, 2% manganese, 0.04% berylium, 0.015% carbon, and 15.81% iron. It has a modulus of elasticity of 28,000,000 lb./in.^{2} and depending upon hardness, has a yield strength of up to 310,000 lb./in.^{2}. Although Elgiloy is marketed in four tempers (resiliences), the spring characteristics are similar to stainless steel (Burstone and Goldberg, 1980).

A nickel-titanium alloy was developed by William Buehler for the U.S. Navy in the early 60´s and "Nitinol" wire was marketed by Unitek Corp., Monrovia, CA in the early 70´s. This material is composed of 52% nickel, 45% titanium, and 3% cobalt and has a modulus of elasticity of 4,800,000 lb./in.^{2} (about one-sixth that of stainless-steel) and a typical yield strength of 230,000 to 250,000 lb./in.^{2} (Andreasen and Morrow, 1978). Andreasen and Barrett (1973) measured and compared stiffnesses in bending for identical cross-sections of Nitinol and stainless-steel wires. They found that the stainless-steel wires required appreciably larger force magnitudes than corresponding Nitinol wires to produce a predetermined amount of deflection. Clinical use of Nitinol since 1972 has led to the following conclusions among clinicians and researchers: 1) Nitinol requires fewer arch wire changes, 2) requires less chair time, 3) shortens treatment time required to accomplish rotations and leveling, and 4) produces less patient discomfort (Andreasen and Morrow, 1978). Because of Nitinol's low modulus of elasticity and high tensile strength, it can sustain large elastic deflections, making it ideal when large deflections and light forces are desired (Burstone and Goldberg, 1980). An added advantage is that rectangular wire can be inserted early in treatment to allow "simultaneous rotation, leveling, tipping, and torquing" (Andreasen and Morrow, 1978).

There are some drawbacks, however, to the use of Nitinol arch wires. It has low formability due to limited ductility and so is prone to fracture when bent over a sharp edge. First- and second-order bends can be placed in the wire but third-order bends are not usually even considered (Kusy, 1981). Nitinol cannot be soldered to or welded without annealing the wire. A third drawback is its high cost and question of future availability of raw materials used in the manufacture of these arch-wires (Kusy and Greenberg, 1981).

Beta-titanium is the newest single-strand wire material available and it is marketed under the trade name "TMA" (Ormco Corp., Glendora, CA). The alloy is composed of 79% titanium, 11% molybdenum, 6% zirconium, and 4% tin-titanium alloy. Its name is derived from a heat treatment that converts the crystalline structure of the titanium to that referred to as the "beta-stabilized phase" (Burstone and Goldberg, 1980). This alloy possesses a modulus of elasticity of 9,400,000 lb./in.^{2} and an as-received yield strength of 170,000 lb./in.^{2}. Desirable characteristics of TMA wire include decreased flexural stiffness and increased elastic range as compared to stainless-steel wire of the same size, excellent formability, and weldability, Because of its intermediate elastic modulus between stainless steel and Nitinol, this wire material is ideal in applications where an intermediate force magnitude is desired (Burstone and Goldberg, 1980). The major drawbacks to TMA wire are its cost and the question of future availability of raw materials required for its manufacture.

The most recent group of arch wires exhibiting reduced stiffnesses and increased elastic ranges as compared to solid stainless-steel wires are the multistrand wires. These wires consist of multiple stainless-steel fibers, and wires are available in three up to twelve individual fibers with simple twist formats for the three-strand, co-axial designs for the five and six-strand wires, and braided patterns for the eight, nine, and twelve-strand wires. Multistrand wires have the advantage of small strand cross-sections which yield higher maximum elastic deflections with relatively low stiffnesses (Burstone, 1981). Thurow (1982) states that "multiple straight strands keep the same working range as a single strand while stiffness and strength are additive as strands are added". In an attempt to quantify stiffnesses and elastic ranges of multistrand wires, Cohen (1984) found that Thurow's predicted values did not account for differences in braid pattern or interstrand friction associated with his testing procedure (a modified version of the flexure test within A.D.A. Specification No. 32). Cohen suggested that elastic properties of multistrand arch wire be done primarily by direct experimentation due to the inadequacy of existing theory to predict characteristic values.

The Structural Mechanism

As a structural system the orthodontic appliance consists intraorally of bands or bonded pads and the attached brackets, the arch wires, the ligatures, and any intra-arch or inter-arch connective elements or auxiliaries such as springs or elastic modules (Nikolai, 1978). The function of the orthodontic appliance is to displace one or more teeth by forces transmitted from the arch wires and attachments to the brackets. The arch wire is the primary means of force delivery in most situations. Using engineering beam analysis, arch-wire characteristics can be quantified. Thurow (1982) states that "to an engineer, any slender structure that is subjected to a lateral (bending) load is a beam". Since an arch wire obviously may correspond to this definition, it is apparent why engineering beam theory is increasingly being used to describe and compare orthodontic arch-wire elastic properties.

History of Orthodontic Wire Specifications

Evaluation of orthodontic arch wires using engineering beam theory is a relatively recent development. Until 1932 there was no set of standards for manufacturing or marketing of othodontic wires. A committee composed of members of the Gold Section of the American Trade Association met in 1929 for the purpose of publishing physical data and establishing a standard method of testing precious metal products, including arch wires (Crowell, 1932). Paffenbarger, Sweeney, and Isaacs (1932) surveyed physical and chemical properties of commercial alloys and drew up a tenative specification for American Dental Association approval. Specification No. 7 concerning wrought gold wires was approved in September 1932 as proposed by Paffenbarger, Sweeney, and Isaacs (1932). Specification No. 7 directed color requirements and established test procedures for determinations of yield strength, tensile strength, elongation, and fusion temperature using round wire samples between 0.038 and 0.042 in. in diameter. Although the specification was reaffirmed every five years until 1977, it was clearly out of date long before this time. In 1977, the American Dental Association adopted Specification No. 32 for orthodontic wires not containing precious metals and subsequently reaffirmed it in 1982 (Council on Dental Materials and Devices, 1977). This specification gave identification and marketing information as well as established test procedures for quantifying specific wire material properties in bending, partially using engineering beam theory.′ The results of these tests enabled comparisons of wire samples and their properties within a standardized format.

The flexure tests within A.D.A. Specification No. 32 direct quantification of yield strength, modulus of elasticity (using a Tinius Olsen stiffness tester), and resistance to reversed cold bending from the average of three or more of a series of five specimens. The Specification was designed for wires of the early 1970′s: single-strand wires with high material stiffnesses and moderate to high ductility. Using the modified cantilever format at the one-inch test span, inelastic behavior of many of the solid steel and Elgiloy test specimens begin at relatively small deflections; however, ranges of the elastic moduli (a constant material property!) started to appear in the literature for some of the lighter stainless-steel and chrome-cobalt wires (Brantley, Augat, Myers, and

Winders, 1978). Yoshikawa, Burstone, Goldberg, and Morton (1981) examined the problem and found that the small-deflection theory used in determining flexure modulus was not compatible with the large deflections observed with the lighter orthodontic wires. The availability of the titanium-based alloys and multistrands compounded problems. The highly resilient and flexible specimens often became unstable with increasing angular deflections and slid off the knife-edge before the yield-point was reached (Cohen, 1984). In a attempt to quantify elastic properties, some researchers began to modify the test protocol; Burstone and Goldberg (1983) reduced the test span to ten and five millimeters. Cohen (1984) ran his experiments at test spans of twelve and six millimeters and was still unable to determine the range for several of the lighter Nitinol and multistrand wires.

Proposed Flexure Test

Specification No. 32 quantifies mechanical properties on a per-unit-volume basis which is difficult for the typical clinician to interpret without the understanding of engineering formulas. Accordingly, the proposed format would determine structural stiffnesses in grams of force per millimeter of deflection (rather than elastic moduli) and elastic ranges in millimeters (in place of yield strengths). Stiffness, when multiplied by the activating deflection, gives the initial force magnitude in clinical application as well as the rate of force decay as gradual deactivation occurs as a result of tooth movement at the support site. Determination of stiffness would eliminate the need of theoretical formulas, of questionable validity, to determine elastic moduli for each material. Thurow (1982) states that "modulus of elasticity is of practically no value as a criterion for selecting one material over another. It merely indicates ease of stretching which is related to ease of bending". The key parameter to wire selection is stiffness or load-deflection rate (Burstone, 1981).

The purpose of this study, then, was to develop a new elastic bending-test format that would allow attainment of specific, clinically relevant, elastic properties without excessive deflection. A split-anchorage format with midspan activation and partial rotational constraints at either end of the wire specimen should allow all data-gathering with moderate transverse deflections. By replacing the knife-edge support which imposes no rotational constraints with bracket-simulating supports, range decreases and stiffness increases compared to parametric values obtained using A.D.A. Specification No. 32 testing protocol. The proposed bending format was evaluated in a series of bench tests to determine the structural properties of stiffness and elastic range of currently available single-strand archwires. Independent variables of interest in addition to material composition were cross-section, span, and support width. Values obtained were then compared subsample to subsample and to theoretical and experimentally determined values from previously published research.

CHAPTER III

METHODS AND MATERIALS

Introduction

A principal purpose of this investigation was to evaluate an alternative static-bending-test configuration to that within the present A.D.A. Specification No. 32. The modified cantilever was replaced with a split-anchorage format with bracket-simulating, restricted rotations at the supports yielding smaller characteristic deformations. Wire specimens of nickel titanium, beta titanium, and stainless steel alloys were tested to determine structural properties of stiffness (rather than elastic moduli) and elastic range (in millimeters, instead of yield strengths). The test results were then intercompared and examined next to published values obtained through use of the present Specification No. 32 or modifications of it.

Test Apparatus

Thurow (1982) suggests that orthodontic wires should be evaluated by simulated-use tests that measure actual performance required in service. A portion of

A.D.A. Specification No. 32 directs the quantification of several properties from orthodontic wire activated as a cantilever beam (illustrated in Figure 3-1). Figure 3-2 illustrates the test format used in this study. Test wires were placed between supports and transversely loaded at midspan by a single point contact. The split anchorage arrangement provided rotational constraints at the ends of the wire by simulated bracket slots. The wire specimen was loaded in equal increments from a passive state to a point well beyond the elastic limit. Figure 3-3 illustrates a typical load-deformation diagram.

The test apparatus and the research project were designed to enable determinations of transverse, midspan stiffnesses and elastic ranges of the highly resilient titanium alloy wires; the latter values are not readily obtainable within the present A.D.A. Specification No. 32. Figure 3-4A shows an overall side view of the test fixture including the cantilevered support with integral combination weight basket and load-application tip. Figure 3-5B provides a close front view showing the adjustable support widths, span length, and "slot" sizes. The "force load" of Figure 3-2 is generated by weights placed in the basket and transmitted to the wire specimen through the load tip.

The amount of midspan deflection was quantified with a depth micrometer; measurements were taken

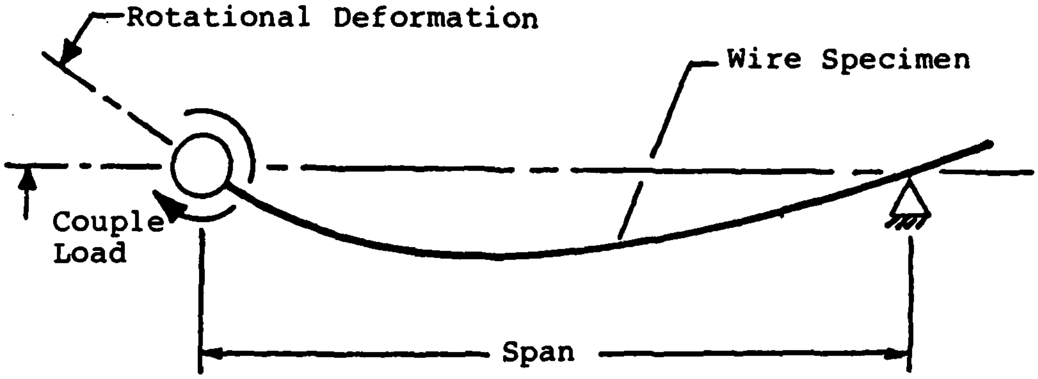


Figure 3-1

Current Flexure Test Format of A.D.A. Specification No. 32

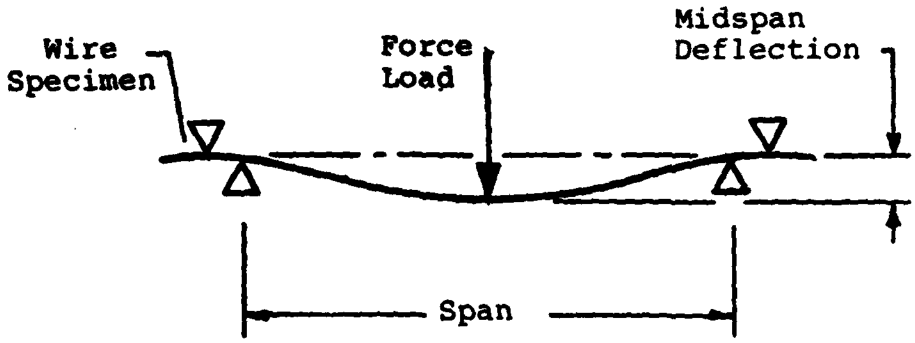


Figure 3-2

Proposed, Alternative Flexure Test

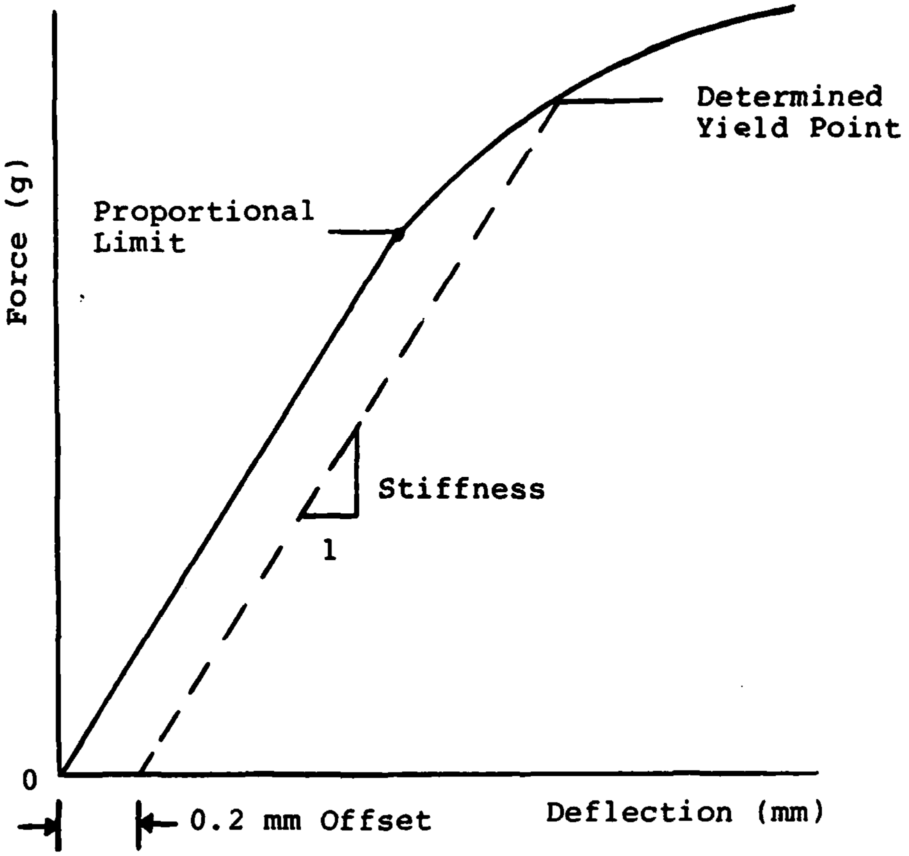


Figure 3-3

Characteristic Force-Deformation Diagram

Figure 3-4A

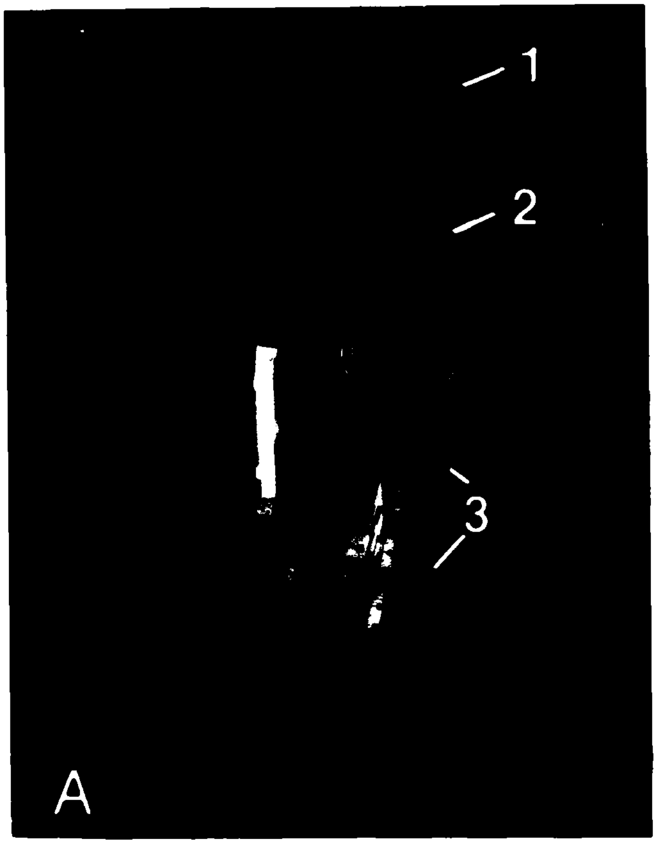
Overall Side View of Test Fixture

1. Weight Basket 2. Support 3. Span Adjustment Screws

Figure 3-5B

Front View of Test Fixture

1. Adjustable Support Widths 2. Adjustable Span Length 3. Slot Width Adjustment 4. Load Tip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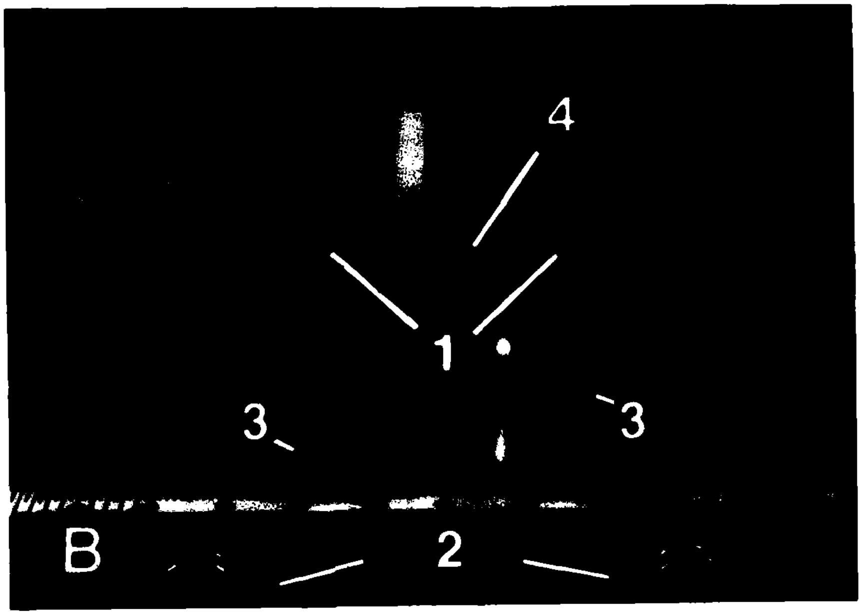
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between the top horizontal surface of the weight basket and a fixed reference surface of the cantilevered support for the basket. Differences in micrometer readings, before and after the addition of each load increment, gave the corresponding deflection increment (Figure 3-6).

Independent Variables

In attempting to modify the format of the static bending test portion of A.D.A. Specification No. 32, structural stiffness and elastic-range were chosen as the dependent variables. The independent variables studied were wire material, cross-sectional shape and size, span length, and support (bracket) width.

Table 3-1 lists the chosen sample of wires. This sample contained a representative selection of wires used for leveling, working, and stabilizing procedures with the 0.22 in. slot-width, orthodontic appliance. All wire was obtained directly from the vendors. Some wire was supplied in straight lengths; other was available only as preformed arches. Two-inch test segments were cut from the straight lengths. Each posterior straight portion of a preformed arch yielded one, two-inch test segment. Straight lengths were received for all stainless steel and the 0.019 in. x 0.025 in. nickel-titanium specimens. The remaining nickel-titanium and beta-titanium materials were

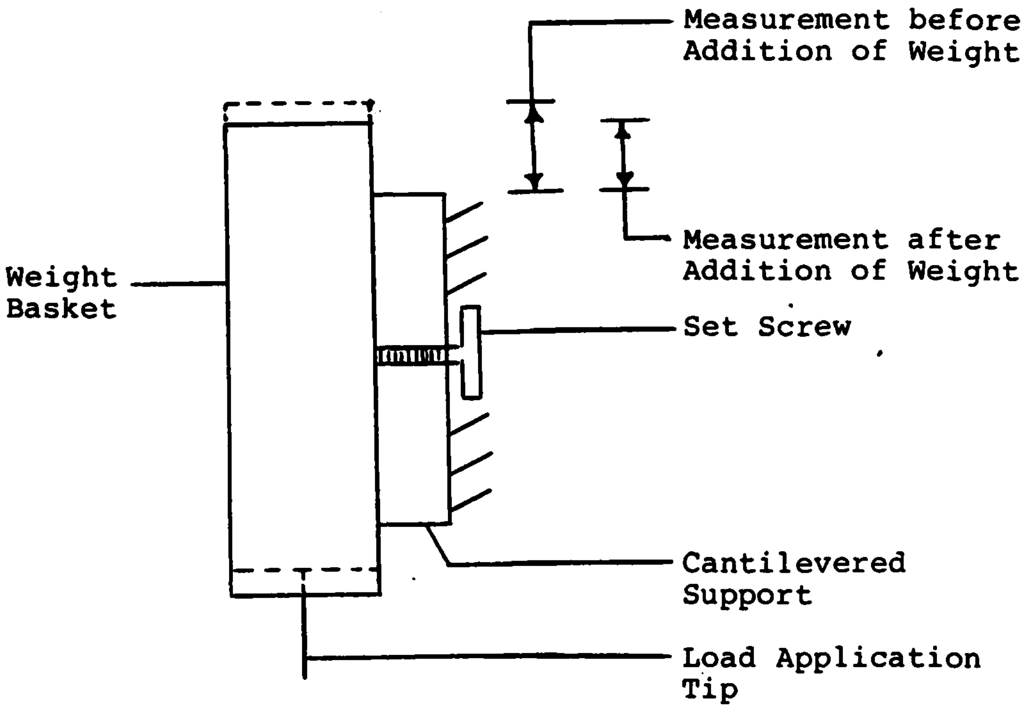

Figure 3-6

Schematic of Weight Basket and Support

TABLE 3-1

Wire Subsample

Alloy (Trade Name)	Size (in.)	Vendor
Nickel-Titanium (Nitinol)	0.016	Unitek
Nickel-Titanium (Nitinol)	0.018	Unitek
Nickel-Titanium (Nitinol)	0.019 x 0.025	Unitek
Nickel-Titanium (Nitinol)	0.021 x 0.025	Unitek
Beta-Titanium (TMA)	0.016	Ormco
Beta-Titanium (TMA)	0.018	Ormco
Beta-Titanium (TMA)	0.019 x 0.025	Ormco
Beta-Titanium (TMA)	0.021 x 0.025	Ormco
Stainless Steel (Standard)	0.016	American
Stainless Steel (Standard)	0.018	American
Stainless Steel (Standard)	0.019 x 0.025	American
Stainless Steel (Standard)	0.021 x 0.025	American

supplied in pre-formed arches. Following the cutting of specimens, no fabrication (bending, twisting) preceded testing.

Each wire subsample was tested at half-span lengths of 10 and 15 millimeters and mesial-distal "slot" widths of 1.5 and 4.5 millimeters. The total number of tests was 288 (three materials x four cross-sections x two spans x two support widths x six replications). No specimen was reused.

The testing sequence was partially ordered by dividing the sample into four groups by span and support width to minimize operator error involved in changing the test machine settings for each specimen (Table 3-2). Each group included 72 tests (twelve wire subsamples with six replications). The sequence of individual tests within each group was randomized. Coded tags designating the twelve subsamples were prepared and, individually, blindly drawn and the appropriate specimen was then tested. This procedure was repeated until six replications of each subsample was completed. The machine was then set at the support width and span of the next group and the procedure repeated until all specimens of the four groups had been tested.

It was necessary to do pilot tests for each group to approximate the elastic limit for each subsample. A specimen from each subsample was activated in equal increments and the corresponding deflection

TABLE 3-2

Test Sequence According to Span and Support Width

Sequence	Half-span (mm)	Support Width (mm)
First	10	1.5
Second	10	4.5
Third	15	4.5
Fourth	15	1.5

measured until inelastic behavior occurred. The load was then removed and the permanent set measured. A minimum of 0.2 mm of permanent deformation was required to validate that the maximum load exceeded the elastic limit of the specimen. The pilot tests thus served as guidelines to establish load increments for subsamples within each group. Flexural deflections within and beyond the elastic range could then be expected for any specimen tested.

The Individual Test

The typical, randomly-chosen wire was placed in the supports and centered with respect to the midspan activation point. The load application tip of the weight basket was positioned to just touch the wire specimen and the set screw in the cantilevered support tightened against the weight basket cylinder. The zero load-deflection reference reading was taken with the depth micrometer (Fig. 3-6) to the nearest 0.01 millimeter and recorded on the data sheet (Figure 3-7). The initial load was the weight of the empty weight basket and attached load application tip (26 g); equal load increments established by the pilot study were added sequentially. The test fixture was gently tapped following each load increment to reduce the effect of residual frictional forces between specimen and the supports. Following addition of the last load

Specimen No. ________ Test Date ________________

Investigator: ☐ Dr. Anderson ☐ Dr. Messersmith

Wire: ____

Trade Name, Vendor Cross-section Strand(s)

Half Span: ☐ 5 mm ☐ 10 mm ☐ 15 mm

Support Width: ☐ 1.5 mm ☐ 4.5 mm

	Load (g)	Deflection (mm)	Mic Reads (mm)
0.	0	0	
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			

Permanent Set: _________ - _________ = _________ mm

Elastic Curve Regression: Load_e = __________(Defl_e)

Line 1 Eq.: F_1 = _____(D_1 - 0.20) = _____D_1 - _____

Line 2 Equation: F_2 = __________D_2 + ____________

Computed Elastic-limit Coordinates: _____ mm, _____ g

Comments on Specimen/Test: ________________________

____

____

Figure 3-7

Sample Data Sheet

increment, the entire load was removed and the tip was positioned to just touch the specimen. A final reading was taken with the micrometer and subtracted fom the initial reference measurement; the difference was recorded as the permanent set.

Data Reduction

Raw data consisting of a minimum of six data points (force and deflection magnitudes beyond the passive and initial-load states) for each specimen were reduced to yield bending-stiffness and elastic-range values. Figure 3-8 diagramatically illustrates data reduction for one specimen. Stiffness is defined as the slope of the regression line generated from the data points below the elastic range. Elastic range was determined as the abscissa (horizontal component) of the intersection of a second regression line generated by data points just before and after inelastic behavior and a line parallel to but offset 0.2 mm. from the first regression line. It was not possible to surpass the elastic limit for ten of the 288 specimens due to sudden, excessive deflections. As a result, the elastic ranges could not be established for these few specimens.

Multiple analysis of variance was used to statistically examine stiffness and range values for the total sample. Tukey´s Honestly Significant Difference and the Tukey-Kramer Method for unbalanced data were

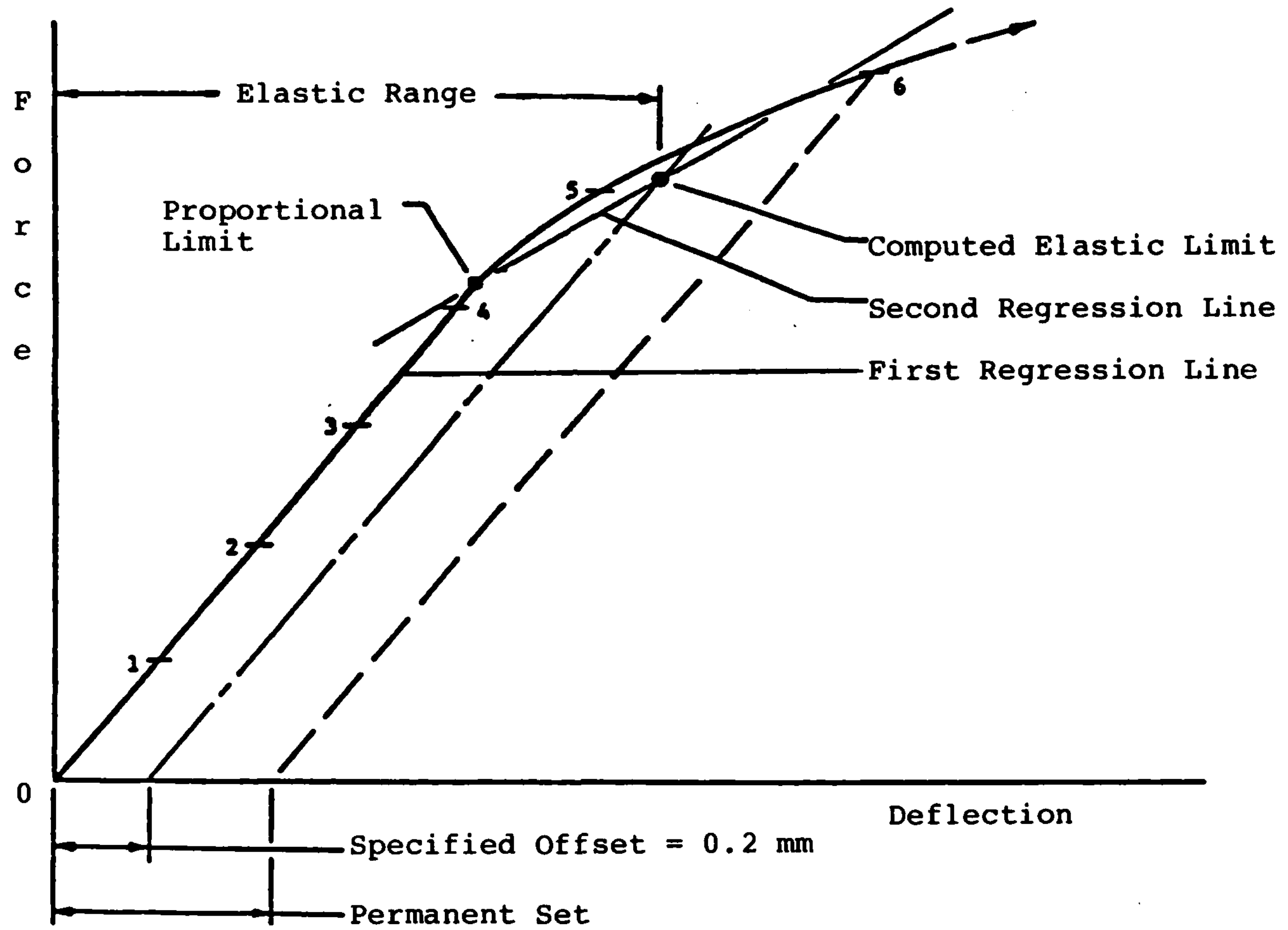

Figure 3-8

Force-Deflection Diagram for One Specimen used to identify individual pairwise differences within an array of means indicated by analysis of variance procedures as including significantly different values.

CHAPTER IV

RESULTS

Data collected from the experimental procedures previously described have been reduced and the statistical analysis is presented in the tables of this chapter. All analysis of variance procedures were accomplished on the St. Louis University Vax 11/750 computer (Digital Equipment Corp., Maynard, MA) using the on-line "SAS" statistical software package. The results are presented partitioned by the dependent variables: flexural stiffnesses, followed by elastic ranges in bending. The first table in each part is a multiple analysis of variance summary table with F-values and probability figures associated with main effects. For example, a probability value of 0.001 indicates the main effect has a statistically significant effect on the dependent variable at the 99.9% confidence level. Two-way interactions are classified as strong, weak, or not present (none).

Following each summary table are tables of mean stiffnesses in bending or mean elastic-range values for the significant main-effects and interactions. Tukey's

"Honestly Significant Difference" test (Kirk, 1968) was used for pairwise comparisons of means of equal subsample sizes. When subsample sizes were unequal the "Tukey- Kramer Method" for unbalanced cells (SAS User's Guide: Statistics, 1982) was used to quantify minimum significant differences. Both tests were referenced to the 99% confidence level.

Table 4-1 is the multiple analysis-of-variance summary table for the complete wire sample for the dependent variable, bending stiffness. Tables 4-2 through 4-6 present mean bending stiffnesses and indications of significant main-effects and interactions.

Table 4-7 lists mean stiffness values for each six-specimen, wire subsample (material, shape and size) at the chosen half-span lengths and support widths.

Table 4-8 is the multiple analysis-of-variance summary table for the dependent variable, elastic range. Tables 4-9 through 4-12 present mean elastic-range values toward verification of significant main-effects and interactions. Unequal subsample sizes are indicated in parenthesis and resulted from failure to exceed the elastic limit for some wire specimens. Ten out of two hundred and eighty-eight tests failed to yield an elastic limit. Failure was defined as inadequate permanent set (less than 0.2 mm upon unloading) or sudden, excessive deformation due to specimen

TABLE 4-1

Analysis of Variance Summary Table: All Wire Subsamples with Bending Stiffness as the Dependent Variable

Source	df	Sum of Squares	Mean Square
Model	47	75800000	1610000
Error	240	476000	1980
Total	287	76300000	

Source of Variance	df	F value	Pr > F
Main Effects			
Material (A)	2	4710	0.0001
Shape and Size (B)	3	3830	0.0001
Span Length (C)	1	6640	0.0001
Support Width (D)	1	278	0.0001
Two-Way Interactions			
A X B	6	670	Strong
A X C	2	1230	Weak
A X D	2	32	Weak
B X C	3	847	None
B X D	3	38	None
C X D	1	26	None

TABLE 4-2

Mean Bending Stiffnesses of All Wires in g/mm: Entire Sample Partitioned by Wire Material and Incorporating Two Spans, Two Support Widths, and Four Cross-Sections

HSD(.01)* = 18.7

Nitinol	170
TMA	413
Stainless Steel	789

* Honestly Significant Difference at the .01 probability level

TABLE 4-3

Mean Bending Stiffnesses of All Wires in g/mm: Entire Sample Partitioned by Wire Cross-Section and Incorporating Two Spans, Two Support Widths, and Three Wire Materials

HSD (.01) = 23.1

0.016 in.	153
0.018 in.	226
0.019 x 0.025 in.	612
0.021 x 0.025 in.	839

TABLE 4-4

Mean Bending Stiffnesses in g/mm: Sample Partitioned by Wire Material and Cross-Section to Exhibit a Two-Way Interaction

HSD (.01) = 48.1

	Nitinol	TMA	Steel
0.016 in.	80.6	140	237
0.018 in.	81.0	219	377
0.019 x 0.025 in.	202	528	1107
0.021 x 0.025 in.	317	765	1436

TABLE 4-5

Mean Bending Stiffnesses in g/mm: Sample Partitioned by Wire Material and Span Length to Exhibit Several, Weak, Two-Way Interactions

HSD (.01) = 0.526

	Nitinol	TMA	S. Steel
10 mm	245	592	1177
15 mm	95	234	401

TABLE 4-6

Mean Bending Stiffnesses in g/mm: Sample Partitioned by Wire Material and Support Width to Exhibit Several, Weak, Two-Way Interactions

HSD (.01) = 30.6

	Nitinol	TMA	Stainless Steel
1.5 mm	196	486	821
4.5 mm	144	340	758

TABLE 4-7

Mean Bending Stiffnesses in g/mm of the Forty-Eight Subsamples

Material	Cross-Section (in.)	Support Width	1.5 mm		4.5 mm	
		Half Span	10 mm	15 mm	10 mm	15 mm
Nitinol	0.016		133	60.9	93.2	34.8
Nitinol	0.018		129	53.7	101	40.1
Nitinol	0.019 x 0.025		322	137	250	96.6
Nitinol	0.021 x 0.025		539	197	389	144
TMA	0.016		226	97.8	173	61.6
TMA	0.018		348	155	279	94.7
TMA	0.019 x 0.025		904	310	644	253
TMA	0.021 x 0.025		1258	588	904	310
Steel	0.016		353	121	364	112
Steel	0.018		575	219	537	178
Steel	0.019 x 0.025		1767	589	1535	535
Steel	0.021 x 0.025		2189	757	2101	699

TABLE 4-8

Analysis of Variance Summary Table: All Wire Subsamples with Elastic Range as the Dependent Variable

Source	df	Sum of Squares	Mean Square
Model	47	495	10.5
Error	230	135	0.6
Total	277	630	

Source of Variance	df	F value	Pr > F
<u>Main Effects</u>			
Material (A)	2	181	0.0001
Shape and Size (B)	3	1.4	0.2293
Span Length (C)	1	318	0.0001
Support Width (D)	1	0.6	0.4603
<u>Two-Way Interactions</u>			
A X B	6	3.41	Strong
A X C	2	8.27	Weak
A X D	2	0.21	None
B X C	3	1.72	Weak
B X D	3	1.16	None
C X D	1	0.42	None

TABLE 4-9

Mean Elastic Ranges of All Wires in mm: Entire Sample Partitioned by Wire Material and Incorporating Two Span Lengths, Two Support Widths, and Four Cross-Sections

HSD and T-K* (.01) Values = 0.322 and 0.328

Nitinol (86)**	4.48
TMA (96)	3.44
Stainless Steel (96)	2.31

* Tukey-Kramer significant difference

** Incorporated number of specimens

TABLE 4-10

Mean Elastic Ranges in mm: Sample Partitioned by Wire Material and Cross-Section to Exhibit Several Two-Way Interactions

HSD and T-K (.01) Values = 0.827 and 0.846

	Nitinol	TMA	S. Steel
0.016 in.	4.15 (17)	3.54 (24)	2.72 (24)
0.018 in.	4.49 (22)	3.45 (24)	2.52 (24)
0.019 x 0.025 in.	4.48 (24)	3.65 (24)	1.86 (24)
0.021 x 0.025 in.	4.73 (23)	3.13 (24)	2.14 (24)

TABLE 4-11

Mean Elastic Ranges in mm: Sample Partitioned by Wire Material and Span Length to Exhibit Several, Weak, Two-Way Interactions

HSD and T-K (.01) Values = 0.526 and 0.537

	Nitinol	TMA	S. Steel
10 mm	3.84 (44)	2.36 (48)	1.57 (48)
15 mm	5.16 (42)	4.53 (48)	3.05 (48)

TABLE 4-12

Mean Elastic Ranges in mm: Sample Partitioned by Wire Cross-Section and Span Length to Exhibit a Weak Two-Way Interaction

HSD and T-K (.01) Values = 0.644 and 0.656

	10mm	15mm
0.016 in.	2.45 (34)	4.44 (31)
0.018 in.	2.72 (35)	4.20 (35)
0.019 x 0.025 in.	2.56 (36)	4.10 (36)
0.021 x 0.025 in.	2.49 (35)	4.12 (36)

instability. As mentioned earlier, pairwise comparison of means of unequal subsample sizes were evaluated by the Tukey-Kramer Method.

Table 4-13 contains mean elastic-range values for each six-specimen wire subsample, collectively including all combinations of the chosen independent variable values.

TABLE 4-13

Mean Elastic Ranges in mm of the Forty-Eight Subsamples

Material	Cross-Section (in.)	Support Width	1.5 mm		4.5 mm	
		Half Span	10 mm	15 mm	10 mm	15 mm
Nitinol	0.016		3.11 (6)*	4.94 (4)	4.00 (4)	5.36 (3)
Nitinol	0.018		4.27 (5)	4.36 (5)	3.96 (6)	5.34 (6)
Nitinol	0.019 x 0.025		4.24 (6)	4.68 (6)	3.72 (6)	5.30 (6)
Nitinol	0.021 x 0.025		4.16 (6)	5.61 (6)	3.28 (5)	5.62 (6)
TMA	0.016		2.40 (6)	4.45 (6)	2.63 (6)	4.71 (6)
TMA	0.018		2.05 (6)	4.88 (6)	2.42 (6)	4.45 (6)
TMA	0.019 x 0.025		2.12 (6)	6.24 (6)	2.57 (6)	3.66 (6)
TMA	0.021 x 0.025		2.04 (6)	3.18 (6)	2.63 (6)	4.69 (6)
Steel	0.016		1.57 (6)	4.52 (6)	1.48 (6)	3.32 (6)
Steel	0.018		1.85 (6)	2.90 (6)	2.01 (6)	3.33 (6)
Steel	0.019 x 0.025		1.07 (6)	2.27 (6)	1.64 (6)	2.44 (6)
Steel	0.021 x 0.025		1.33 (6)	2.97 (6)	1.62 (6)	2.66 (6)

* Number of successful tests

CHAPTER V

DISCUSSION

The purpose of this study was to determine flexural stiffness and elastic-range values for a representative sample of single-strand orthodontic wires using an alternative bending test format to that contained within A.D.A. Specification No. 32. In addition, the influences of material composition, cross-section, test span, and support width on stiffness and range were evaluated.

The contents of this chapter are ordered in a five-part format. Each part contains a discussion of stiffness followed by comments on elastic range. First, the predicted results based on engineering beam theory are given. Second, the experimental findings (Chapter IV) are compared with theoretical predictions. Third, the results of this study are contrasted to other published findings. Fourth, the clinical implications of the actual outcomes and the wire-property relationships as determined from this study are discussed. Fifth, and last, a critique of the test format is given.

Bending Theory

The test format used here is geometrically and mechanically symmetrical with respect to the transverse load line (see Figure 3-2). In this test format, the stiffness of a single-strand orthodontic wire segment is influenced primarily by three parameters: 1) elastic modulus of the material, 2) cross-sectional shape and size, and 3) span. In general terms, flexural stiffness is proportional to elastic modulus and the fourth power of the cross-sectional diameter (round wires) and inversely proportional to the cube of the span. For rectangular wires, stiffness is proportional to the elastic modulus, the third power of the thickness, the first power of the width, and inversely proportional to the cube of the span. When comparing solid wires of the same shape, size, and span, flexural stiffness is most influenced by cross-sectional dimensions followed by span length and material elastic modulus. A fourth parameter that should affect stiffness in the clinical arena is support or bracket width. Most hypotheses to date are concerned with the influence of bracket width on interbracket span and do not directly deal with bracket width alone. In this study, half-span was measured from the activation point to the mesial extent of the "bracket" to enable its independence from bracket width.

Single-strand wires of the same cross-section, and with the same test span and support width, theoretically can be compared in elastic bending, if deflections are small, simply through the material stiffness (elastic-modulus) ratio of the two wires. The theoretical stiffness ratios derived from elastic moduli values of stainless steel, TMA, and Nitinol as given by Kusy and Greenberg (1982) are approximately 6.6:2.0:1.0.

Elastic range is theoretically affected by four parameters: 1) elastic-limit bending stress, 2) span, 3) modulus of elasticity, and 4) cross-sectional shape and size. Elastic range is proportional to the elastic-limit bending stress and the square of the span and inversely proportional to the first power of the elastic modulus and the diameter or cross-sectional depth if deflections are small. The effect of support width on range has not been included in current theoretical formulas. Clinically, the most influential parameter affecting range is material elastic modulus followed by span length and elastic-limit stress. Due to the dominant influence of elastic modulus, the ranking of ranges partitioned by material should be reversed from that of stiffnesses. The theoretical range ratios as derived from nomograms published by Kusy (1983) are 0.3:0.5:1.0 for stainless steel, TMA, and Nitinol wires of alike cross-sections and test lengths, respectively.

Experimental Results: Stiffness

The summary table (Table 4-1) of the analysis of variance reveals statistically significant differences in stiffness magnitudes attributable to each of the main effects (independent variables). Potential two-way interactions were examined using the appropriate pair-wise statistic and classified as strong, weak, or none (not present).

Table 4-2 contains the mean bending stiffnesses for the 288 specimens partitioned by material. The ranking is in agreement with theory which suggests that stiffness increases as the elastic modulus of the material increases. Each of the three pair-wise differences was verified as statistically significant at the 99% level of confidence. The experimentally determined ratios of mean bending stiffnesses were 4.6:1.9:1.0 for the entire steel, TMA, and Nitinol subsamples, respectively. These differed from the theoretical predictions of the elastic-modulus ratios of 6.6:2.0:1.0 and suggest that the relative stiffness values for TMA and Nitinol may in theory be too low compared to steel. The ratio of TMA to Nitinol is close to what theory would predict which supports the possibility of inflated stiffness values for TMA and Nitinol wires. The most likely reason for the decreased experimental stiffness ratios is a combination of two factors not included in the theoretical formulas.

First, the formulas do not account for the presence of friction which experimentally causes an increase in stiffness values. Second, present theory is based on the assumption of small deflections. In this study, many of the Nitinol and TMA specimens experienced large deflections compared to their stainless-steel counterparts when the elastic limit was being determined. The results of large-deflection corrections of small-deflection formulas are stiffness values that are lower than predictions made by small-deflection theory.

Frictional force depends on three primary factors: 1) the relative roughness of the two surfaces in contact; 2) the "normal" or perpendicular force between the contacting surfaces; and, least understood, 3) the contact area between surfaces. Most brackets and wires are fairly smooth and the most important variable is the force generated between the wire and knife-edge supports when the load is applied. Some wire materials may have rougher surfaces which would increase frictional forces and result in apparent increases in experimentally determined stiffnesses. Edie, Andreasen, and Zaytoun (1981) reported that stainless-steel wires are generally smoother than Nitinol wires which have a "bubbling" or "mottled cake" appearance. Since TMA is a titanium alloy, like Nitinol, it may also have a rougher surface than steel. Surface roughness may account for some of the discrepancy between the results of this study and theory although frictional forces were "broken" by lightly tapping the test fixture throughout data gathering. The normal force of the wire against the knife-edge supports depended on the magnitude of the load applied toward reaching the elastic limit. As the load increases, the normal and resulting frictional forces increase. An oversimplification is that stiffer wires generate more frictional force. Contact area, in this study, refers to a site where the wire specimen touches the knife-edge supports. Round wires develop point contacts while rectangular cross-sections make line contacts with the knife-edge supports. For given round and rectangular wires loaded identically, frictional forces are more concentrated at the point contact against the round wire than at the line contact of the rectangular wire. The net result can be increased frictional resistance for the round specimen compared to rectangular wire, particularly if the knife-edge indents the former.

The formulas used for determining theoretical elastic moduli can be in error as shown by Yoshikawa, Burstone, Goldberg, and Morton (1981). When wires are evaluated using the cantilever flexure test in A.D.A. Specification No. 32, the elastic moduli are computed from formulas assuming small deflections. In testing, the highly flexible wire specimens may undergo substantial deflections and thereby increase the actual length of wire between the supports. The result is potentially erronously low values for calculated elastic moduli unless the excess wire length between the supports is considered in the formula for elastic moduli. The shortcoming is also present in the formulas used to determine theoretical stiffness and elastic-range values using a bending format similar to the proposed test. These formulas, previously discussed under bending theory, are based on small deflections which are generally applicable to the larger steel wires but not for many of the Nitinol and TMA wires which experience sizable deflections. Small-deflection theory predicts artificially high stiffnesses and low elastic ranges for wire beams experiencing large transverse deformations.

Table 4-3 confirms the expected prominent influence on flexural stiffness of cross-sectional size. Mean bending stiffnesses ranked as predicted from theory and significant pair-wise differences were found in each comparison of cross-sections. The increase in stiffness was greatest between the 0.018 in. and the .019 x .025 in. cross-sections. This is due to the increase in cross-sectional dimensions and, in particular, the effect of increased area, rectangular versus round shape.

The main effects of span and support width highly influenced stiffnesses as indicated by the probability values in Table 4-1. When half-span length was increased from 10 mm to 15 mm, stiffness decreased substantially. When support width increased from 1.5 mm to 4.5 mm, stiffness also decreased significantly. The amount of and rationale for stiffness change caused by these two independent variables is discussed in greater detail later in this chapter.

The only strong two-way interaction involving main-effect influences on stiffness is presented in Table 4-4 where the sample is partitioned by both material and cross-section. Mean bending stiffness ranked with respect to material emerged as predicted by theory; however, mean bending stiffness values obtained from the .016 and .018 in. Nitinol wire tests were essentially identical. As mentioned previously, friction "locks" were broken by gentle tapping on the test fixture throughout the test procedure. The identical stiffness values for the smallest Nitinol wires suggest that friction may still have overridden the influence of diameter for the lightest Nitinol wire, resulting in an inflated mean stiffness value.

Table 4-5 contains several weak interactions between wire material and span length in their collective influence on stiffness. The first noted is the difference in the rate of decrease in mean stiffness by material as the half span was increased from 10 to 15 mm. The steel specimens experienced a more pronounced decrease in stiffness compared to the Nitinol and TMA test wire segments. This is probably due to the relatively smooth surface of steel. Frictional forces have relatively more influence on stiffness values of lighter wire segments. A second weak interaction is the rate of stiffness increase, individually at the 10 and 15 mm half spans, from TMA to steel as compared to Nitinol to TMA. The lower rate of increase from TMA to steel at the 15 mm half span, together with similar stiffness ratios between the titanium-alloy wires at the two spans, suggest that the TMA wire surfaces have roughnesses comparable to those of the Nitinol wires.

Table 4-6 contains several weak interactions between wire material and support width. Rank order emerged as predicted by theory for material but theory does not account for support width influence on stiffness. As seen in Table 4-6, support width had an inverse effect on stiffness. In this test format, as the load was applied, the upper knife-edge support restrained wire movement in a manner very similar to that of a typical bracket. A couple is generated, as part of the response, between the knife-edge supports and the segment that, in magnitude, varies inversely with support width. The narrower supports produced larger pairs of opposing normal forces. As discussed earlier, as the normal force increases, friction increases and also stiffness. A weak interaction is also present among materials dependent on support width. The increase in bracket width from 1.5 to 4.5 mm decreased mean stiffnesses of the steel specimens at a lower rate than for the Nitinol and TMA wire segments. Again, this reflects the lower frictional influence of the smoother material which results in a smaller rate of change. A second interaction in the table involved the specimens partitioned by material at the 1.5 mm support width. The difference in stiffnesses between the steel and the TMA specimens was not as great as expected. The greater surface roughness of TMA compared to the steel specimens produced greater frictional differential with the narrower support width (and the higher normal responsive forces).

Table 4-7 presents mean bending stiffnesses of the forty-eight, six-specimen subsamples and allows a relative comparison of stiffness values determined by material, cross-sectional shape and size, span length, and support width. According to theory, stiffness is inversely proportional to the cube of the span. Using half-span lengths of 10 and 15 mm gives a theoretical stiffness ratio of 3.4:1 for otherwise alike wire specimens. As mentioned previously, half span was measured from the knife-edge closest to the load tip to the load tip itself. The actual span, and that assumed in theory, is the distance between the midpoints of the support sites. By adding the support widths together and dividing by two to get a mean support width of 3 mm, the actual mean half spans employed were 13 and 18 mm, and $(18/13)^3$ yields the "true" theoretical ratio of 2.7:1.0. Mean bending stiffnesses partitioned by span alone yielded a ratio of 2.8:1.0. The experimental ratio is slightly higher than predicted due to increased frictional effects at the smaller span resulting from higher normal forces.

The main effect of support width was highly significant as indicated by the probability value seen in the Summary Table 4-1, and, as noted in the discussion of Table 4-6. A substantial decrease in stiffnesses for each six-specimen wire group is apparent in Table 4-7 when the support width is increased from 1.5 to 4.5 mm.

Experimental Results: Elastic Range

The Summary Table 4-8 for variances in elastic range reveals that just two of the four independent variables studied, material and span length, significantly influenced range values experimentally determined.

Table 4-9 contains mean elastic-range values with the sample partitioned by material. The ranking of Nitinol, TMA, and stainless steel are in agreement with theory but range ratios differ from predictions. The experimentally-determined elastic-range ratios for stainless steel, TMA, and Nitinol wires respectively, were 0.5:0.8:1.0. This compares to theoretical values derived from nomograms of Kusy (1983) of 0.3:0.5:1.0. As stated earlier, one of the variables affecting range is elastic-limit bending stress (s_{el}) which is associated in part with the relative ductility of the wire. Kusy´s nomograms apparently base s_{el} for stainless steel on the value provided by a vendor (GAC International) and used in a previous study (Kusy and Greenberg, 1981). Steel wires are manufactured by many companies which may use differing drawing and intermittent heat-treatment procedures which can affect the magnitude of s_{el}. Nitinol and TMA wires are likely produced by separate, individual manufacturers and, although small differences associated with size and manufacturing are possible, the values given by the vendors for s_{el} probably vary little, individually, across all Nitinol and TMA wires. The discrepancy between the experimental ratios of this study and the theoretical ratios of Kusy may be partially due to unlike s_{el} values for steel specimens between the two studies.

Elastic range is fundamentally related to midspan curvature of the wire which varies directly with load magnitude. Any impedance to wire curvature under load reduces the range. Frictional forces likely affect predicted range, but, their influence is at the supports and somewhat distant from midspan. Kusy (1983) used small-deflection theory to predict elastic-range ratios among steel, TMA, and Nitinol wires (0.3:0.5:1.0). Low elastic-range ratios relative to steel resulted as large deflections characteristic for Nitinol and TMA wires are not accounted for in this theory. Mathematically, compensation for the large deflections is roughly in the form of a multiplier greater than unity appended to the numerator of the range formula. This constant accounts for the increase in actual segment length between the supports for those wire beams which experience large deflections. As a result, theoretical range values increase. Correcting Kusy´s ratios for the large deflections of Nitinol and TMA should result in ratios comparable to the experimental results of this study: 0.5:0.8:1.0. Any remaining difference between ratios is associated with support site friction in the present study.

The main-effect influence of span on elastic range was highly statistically significant according to the analysis-of-variance results of Table 4-8. Mean elastic ranges, across all materials, cross-sectional shapes and sizes, and support widths, were 2.55 mm at the "10 mm half span" and 4.21 mm at the "15 mm half span". The theoretical range ratio based on the actual mean half spans employed of 13 and 18 mm, is 1.9:1.0

which compares favorably with the experimental ratio of 1.7:1.0. The small difference between theoretical and experimental ratios is a combination of greater frictional influence on range at the shorter span and the presence of large deflections at the longer span; both not compensated for by theory.

The only strong two-way interactions present in the range analysis are found in Table 4-10 for the test sample partitioned by material and cross-section. There was no significant difference between the .016 in. Nitinol and .016 in. TMA wire ranges. The lack of a highly significant difference between the smallest titanium-alloy wires appears to be a function of an undue relative influence of friction on the lightest wire tested with a resultant relative decrease in its range. No significant differences in range, within materials, were present by cross-section with the exception of the .016 in. and .019 x .025 in. steel specimens. Range means for all other combinations of steel wires were not significantly different from a statistical standpoint.

Table 4-11 contains several weak interactions with the test sample partitioned by material and span. Rank order by material and span conforms to theory but the quantitative difference in range values by span is relatively small for Nitinol wires. The two weak interactions seen in Table 4-11 are both attributable to the presence of large deflections. A greater percentage of large deflections occurred for the lightest wires at the longer span. Lighter wires are most affected by frictional forces and it appears that the range values for Nitinol at the 15 mm half span were suppressed.

The influence of span length on range is also explicit in Table 4-12 where reducted data is partitioned by cross-section and span. Although theoretical predictions of span influence are not attained, the rate of increase in range is greater for the 0.016-in.-diameter test segments as compared to the other cross-sections. This weak interaction may be due to the lower frictional force influences generally present in reaching the elastic limit for the smallest cross-sections compared to the larger test specimens.

Table 4-13 contains the mean elastic ranges of the forty-eight subsamples and the number of successful range determinations per subsample. The expected influence of span length on elastic range is apparent, but no clear trend is evident with respect to support width. Friction and large deflections have opposing effects on range values partitioned by support width and tend to cancel one another.

Results from Other Studies

Stiffness magnitudes obtained in this study and other comparable published research involving Nitinol, TMA, and stainless-steel wires are ranked in Table 5-1. Stiffness rankings are given as it would not be appropriate to compare actual stiffness values, whether normalized to a common wire or not, from studies using different flexure-test designs.

Cohen (1984) experimentally determined bending stiffness values using a modified Specification No. 32 protocol for a representative selection of Nitinol, TMA, and stainless-steel wire cross-sections. Burstone (1981) developed wire stiffness numbers using the product of a material stiffness number (E) and a cross-section number (I). Wire stiffness numbers were assigned to Nitinol, TMA, and stainless-steel segments based on theoretical extensions of unpublished bending-test data from ..016 in. wires of the three materials. Burstone´s rankings compare favorably with Cohen´s results except for a rank reversal of one pair of wires. The results of this study are in agreement with Burstone´s theoretical predictions with the exception of several wires of "intermediate" stiffnesses. The results difference in this study and Burstone´s might be resolved by determining if Burstone assumed small- or large-deflections in obtaining his theoretical values for wires based on the experimental results of the .016-in.-diameter wires. The cantilever test of Cohen (1984) actually represents one-half of a simply-supported beam. Cohen´s protocol, then, is

TABLE 5-1

Rankings of Reported Bending Stiffnesses Ordered by Increasing Stiffness

Material	Cross-Section (in.)	Messersmith	Cohen	Burstone	Kusy
Nitinol	0.016	1	1	1	1
Nitinol	0.018	2	2	2	2
TMA	0.016	3	3	3	3
Nitinol	0.019 x 0.025	4	5	6	5
TMA	0.018	5	4	4	4
Steel	0.016	6	6	5	6
Nitinol	0.021 x 0.025	7	-	8	-
Steel	0.018	8	7	7	7 tie
TMA	0.019 x 0.025	9	8	9	7 tie
TMA	0.021 x 0.025	10	-	10	-
Steel	0.019 x 0.025	11	9	11	8
Steel	0.021 x 0.025	12	-	12	-

Author´s stiffness rankings from 10 mm half-span and 4.5 mm support-width data.

partially comparable to the format of the present investigation, but the difference between rotationally constrained and unconstrained supports, and in span lengths, profoundly affect absolute values and ratios of stiffnesses. The theoretical formulas used to determine both stiffness and range for these two formats are directly related.

Kusy (1981, 1983) and Kusy and Greenberg (1982) published stiffness, range, and strength ratios derived from theoretical formulas for several Nitinol, TMA, and steel wires. The ranking of their stiffness predictions is presented in Table 5-1, and is identical to the ranking of Cohen and, with the exception of one reversal, identical to that of this study.

Comparisons of the stiffness ratios of this study to theory is important because it illustrates the differences that result from inclusion versus exclusion of friction as well as actual large-deflections versus formulas developed for small-deflection data. Frictional forces can dramatically affect stiffness values as discussed earlier in this chapter, and this is substantiated by a look at relative material-stiffness ratios from the four studies listed in Table 5-2. The purely theoretical stiffness ratios of Kusy neglect any presence of friction and accordingly differ from experimental results. Additionally, Kusy's theoretical formulas inherently assume small deflections which are

TABLE 5-2

Reported "E" Ratios of 0.016 Inch Wire Segments

Study		Steel: TMA: Nitinol
Messersmith		2.9 : 1.7 : 1.0
Cohen		3.9 : 2.0 : 1.0
Burstone		4.0 : 1.6 : 1.0
Kusy		6.6 : 2.0 : 1.0
Schaus		2.3 : 1.4 : 1.0
Messersmith	(Entire Sample)	4.6 : 1.9 : 1.0

not typical for the majority of the wires tested using Specification No. 32 protocol when stiffness and elastic-range values are sought concurrently.

The effect of friction on stiffness is even more apparent when just the elastic-moduli ratios of the 0.16-in.-wire subsample from this study are compared to theoretical expectations. The present .016 in. "E" ratios are much lower than predicted by theory and tend to agree with findings of Schaus (1983) who reported the lowest elastic-moduli ratios to date. The thesis investigation of Schaus was a clinically-oriented bench test that studied the influence on stiffness of interbracket length, arch curvature, and direction of force activation. The findings of Schaus and this study demonstrate that the roles of friction and large deformations must be addressed and that comparisons of wire properties should be based on test procedures that closely approximate actual clinical conditions.

Kusy (1983) published nomograms containing stiffness, strength, and range ratios for Nitinol, TMA, and steel wires. These elastic-range ratios normalized to comparable cross-sections are presented in Table 5-3 along with range ratios experimentally derived from the modified Specification No. 32 test format of Cohen (1984) and the protocol of this study. According to Kusy´s theory, Nitinol has twice the working range of corresponding TMA wires; it has just 1.25 times the

TABLE 5-3

Reported Elastic Range Ratios

Study	Steel: TMA: Nitinol
Messersmith	0.5 : 0.8 : 1.0
Cohen	0.6 : 0.8 : 1.0
Kusy	0.3 : 0.5 : 1.0

range based on two separate bench studies. An even greater contrast is apparent between Nitinol and steel. The predicted 3.3:1 range ratio (Kusy) of Nitinol wire to corresponding steel wire was found to be 1.7:1 in Cohen´s work and 2.0:1.0 in this study. The difference between Cohen´s and this study versus Kusy´s can be attributed to frictional interferences at the support sites as well as the presence of large-deflection data for many of the more flexible wires. Cohen´s experimental ratio was smaller than the ratio from this study due to his smaller span lengths.

Clinical Applications

The use of highly flexible wires to deliver lighter forces under larger deflections than conventional single-strand wires has led to a search for a test protocol that would adequately quantify individual wire properties. Table 5-4 contains mean flexural stiffnesses of solid-wire subsamples from this study as well as multistrand steel wires (Anderson, 1985) evaluated using identical test protocol. The wires are ranked in order of increasing flexural stiffness. Table 5-5 contains mean elastic ranges for the same wire subsamples ordered by decreasing range. The test span length common to each study was 20 mm and the 4.5 mm support width was arbitrarily selected for comparisons.

TABLE 5-4

Mean Flexural Stiffnesses: Ordered Results from Two Studies Using 20 mm Span Lengths and 4.5 mm Support Widths

Subsample	Vendor	Cross-section (in.)	Stiffness (g/mm)
6 Strand*	American	.0155	23
6 Strand	TP	.016	25
6 Strand	TP	.018	35
3 Strand	GAC	.015	39
6 Strand	American	.0175	41
3 Strand	GAC	.0175	70
Nitinol	Unitek	.016	93
8 Strand	Ormco	.019 x .025	95
Nitinol	Unitek	.018	101
8 Strand	Ormco	.021 x .025	132
9 Strand	Ormco	.021 x .025	157
TMA	Ormco	.016	173
9 Strand	Ormco	.019 x .025	182
Nitinol	Unitek	.019 x .025	250
TMA	Ormco	.018	279
Steel	American	.016	364
3 Strand	Dentaurum	.019 x .025	372
Nitinol	Unitel	.021 x .025	389
3 Strand	Dentaurum	.021 x .025	501
Steel	American	.018	537
TMA	Ormco	.019 x .025	644
TMA	Ormco	.021 x .025	904
Steel	American	.019 x .025	1535
Steel	American	.021 x .025	2100

* Multistrand wire results from Anderson (1985).

TABLE 5-5

Mean Elastic Ranges: Ordered Results from Two Studies Using 20 mm Span Lengths and 4.5 mm Support Widths

Subsample	Vendor	Cross-section (in.)	Elastic Range (mm)
3 Strand*	GAC	.015	4.88
6 Strand	American	.0155	4.49
6 Strand	TP	.018	4.00
Nitinol	Unitek	.016	4.00
Nitinol	Unitek	.018	3.96
6 Strand	American	.0175	3.84
Nitinol	Unitek	.019 x .025	3.72
8 Strand	Ormco	.019 x .025	3.69
9 Strand	Ormco	.021 x .025	3.63
6 Strand	TP	.016	3.46
8 Strand	Ormco	.021 x .025	3.45
Nitinol	Unitek	.021 x .025	3.28
3 Strand	GAC	.0175	3.13
9 Strand	Ormco	.019 x .025	2.94
TMA	Ormco	.016	2.63
TMA	Ormco	.021 x .025	2.63
TMA	Ormco	.019 x .025	2.57
TMA	Ormco	.018	2.42
3 Strand	Dentaurum	.019 x .025	2.42
3 Strand	Dentaurum	.021 x .025	2.09
Steel	American	.018	2.01
Steel	American	.019 x .025	1.64
Steel	American	.021 x .025	1.62
Steel	American	.016	1.48

* Multistrand wire results from Anderson (1985).

Tables 5-4 and 5-5 provide the clinician with a broad selection of wires from which to select, depending on the force and deflection requirements as well as cross-sectional shape and size limits imposed by the appliance used. Wire selection according to "optimum" force ranges becomes practical with light leveling wires available in rectangular as well as round forms, enabling some early third-order control if needed. The tables also provide the orthodontist with choices based on material rather than just cross-section. If unavailability or high costs precludes the use of titanium-alloy wires, a comparable multistrand wire can be selected.

Stiffness and elastic-range values from this study allow arch-wire selection based on the force magnitude desired for the activating deflection needed. Most clinicians select initial leveling wires based on experience rather than a concerted effort to control force magnitudes within the elastic range of the appliance. As the newer titanium-alloy and multistrand wires were introduced, clinicians continued to base wire selection on experience because available wire elastic-properties provided values of elastic moduli and yield strengths, terms not widely understood by clinicians. In contrast, by using the values of structural stiffness and elastic-limit range from this study (and the multistrand results of Anderson, 1985), the clinician can select wires based on direct experimental values that include the effects of friction and large-deflections as influenced by material, span, cross-sectional dimensions, and "bracket" width. Stiffness, when multiplied by the activating deflection, provides the initial force magnitude as well as the force-decay rate as gradual deactivation results with tooth movement. Elastic range values from this study give the maximum allowable activating deflection tolerable by the appliance without permanent distortion. Both stiffness and elastic range are terms easily understood by clinicians. Of the two, stiffness is most important clinically for force determinations. However, friction had a greater influence on stiffness values in this study and may not be as "accurately" transferred to the clinic as the elastic-range values, which provide maximum-deflection guidelines.

The mean rankings provided in Tables 5-4 and 5-5 demonstrate that multistrand wires typically deliver lower forces and allow slightly larger elastic deflections than comparable single-strand wires of like cross-sections. Stiffness and deflection characteristics of solid and multistrand wires tested under conditions more closely associated with actual use provide the clinician with an improved basis for wire selection.

Critique of Test Protocol

This study emphasizes the practicality of using the flexural properties of structural stiffness and elastic range in appliance analysis. Further changes are perhaps warranted to make the flexure-test format even more clinically-oriented. First, instead of the single load tip, it would be more appropriate to use a pair of knife-edge tips, simulating bracket width at midspan as was done at the support sites. This would be more representative of clinical use and should decrease effective half-spans resulting in lower ranges and higher stiffnesses. Second, span length should be measured from mid-support site to the midpoint of the "bracket-simulating" loading jig. Half span length in this study was measured from the load tip to the mesial edge of the support site in an effort to separately quantify the influence of support width.

From a total of 288 individual tests, ten failures resulted from sudden, excessive deflections. This number should be reduced by employing the pair of load tips to decrease range. In contrast, Cohen (1984) evaluated a similar solid-wire sample using a version of Specification No. 32. Even by employing test spans much smaller than recommended by the Specification, he was unable to control early transverse buckling failures, and as a result could not report mean elastic ranges for the majority of the most flexible wires.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The principal purpose of this investigation was to evalute a clinically-oriented static bending test by determining structural stiffnesses and elastic ranges of a representative selection of orthodontic wires and comparing the obtained values to theoretical predictions and published results based on the present A.D.A. Specification No. 32 or modifications of it.

The independent variables selected for study were material (alloy), cross-sectional shape and size, span length, and support width. The order of testing was randomized within each of four subsample quadrants and a total of 288 tests were completed involving 48 combinations of independent-variable values. Raw test data consisting of force-deflection coordinates were reduced to flexural-stiffness and elastic-range values for each wire specimen. The results were then statistically evaluated through analyses of variance.

The results may be summarized as follows:

1. Rankings of mean bending stiffnesses generally conformed to theoretical predictions but the experimental ratios (steel and TMA to Nitinol) were smaller due to frictional forces at the

support sites and large deflections; both unaccounted for by theory.

2. Rankings of mean elastic ranges were in general agreement with theory, but experimental ratios of range (steel and TMA to Nitinol) were higher than those theoretically predicted due largely to the presence of large deflections.

3. Wire cross-sectional shape and size, as main-effects, generally substantially influenced stiffness as predicted by theory but they did not significantly affect elastic range.

4. Stiffness and range ratios were significantly influenced by span length. Differences between theoretical and experimental ratios due to large deflections were associated with the longer span length.

5. Stiffness varied inversely with support width, but support width did not significantly affect elastic range. Elastic range was apparently not as greatly influenced by friction at the support sites as was stiffness.

6. Experimental values of stiffness and range obtained for the light titanium-alloy wires were most affected by frictional forces and large-deflections. This contributed to the discrepancies between experimental and theoretical ratios and accounted for the few strong interactions present between independent variables.

7. From a total of 288 tests, elastic-limit range values were not obtained for ten of the more flexible specimens due to sudden, excessive deflections. In comparison, Cohen (1984) was unable to quantify range values for the majority of the more flexible titanium-alloy specimens using a variation of Specification No. 32.

The results of this study appear to warrant the following conclusions:

1. Structural comparisons of orthodontic wires should be based on direct experimental results because conventional beam theory does not account for the presence of frictional forces at the support sites or large deflections of the more flexible wires.

2. Stiffness and elastic-range magnitudes determined

from the alternative flexure test are guardedly transferable to the clinical arena--more trustworthy in ratios than in absolute values. Because the influence of friction is less substantial, and the accuracy demanded is lower, more confidence may be placed in the individual elastic-range means than those for stiffnesses.

3. Future research could evaluate force magnitudes during appliance deactivation and determine if stiffness or range values vary with time for wires under constant deflection.

4. The alternative test format with, perhaps, minor modifications, appears to be a logical replacement for the outdated bending-test portion of A.D.A. Specification No. 32.

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