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Load Deformation Test of Mini Twin Metal Brackets : A Comparative Study

Karl D. Peach

ABSTRACT

LOAD DEFORMATION TEST OF MINI TWIN METAL BRACKETS:
A COMPARATIVE STUDY

by

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The trend toward more esthetic brackets has led to smaller brackets being used by orthodontists. The purpose of this study was to determine the force required to deform these smaller brackets and calculate the stress in the metal by using a torsional wire bending force. Ten types of brackets were tested and the results analyzed to determine how bracket geometry, manufacturing method, or material selection affected the strength of brackets. Results showed a significant difference between manufacturing methods, material used, and bracket geometry. Brackets made of 17-4 PH SS and 303 SS withstood higher stress than 316 SS, and all three materials were different for force to deform. Cast, milled, and injection molded/sintered brackets were significantly different for stress to fail; milling and casting were similar to each other, but different from injection molded/sintered for force to deform.

LOMA LINDA UNIVERSITY

Graduate School

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Karl D. Peach

A Thesis in Partial Fulfillment
of the Requirements for the Degree Master of
Science in Orthodontics

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Each person whose signature appears below certifies that this thesis in their opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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INTRODUCTION

In orthodontics, the bracket is recognized as the component by which force from a wire is transmitted to a tooth. A predictable relationship between these two components is necessary for the orthodontist to work effectively with an orthodontic appliance. One such predictable relationship is during the application of lingual root torque to incisors. This relationship can be affected by many variables, including, but not limited to, bracket geometry, manufacturing method, and material selection.[1-15]

Currently the twin bracket design is the most widely used and has been shown to be 1.7 to 3.0 times more effective in delivering force to a tooth than a single wing type bracket.[1] A study of the effect of bracket geometry on internal stress of plastic model brackets showed that larger brackets are significantly stronger in resistance to a torquing force.[2] Mini twin metal brackets (about 30% smaller than a regular twin) have been shown by Choi to be less resistant to a torquing force than regular twin brackets, but the influence of size was less than the influence of material selection.[3] Although these studies would indicate that orthodontists should use larger brackets to avoid deformation of archwire slots, adult patients' demand for more comfortable and esthetic brackets have led manufacturers to actually produce smaller brackets.[5,7]

The bracket manufacturing methods involve various ways of shaping the metal into a useful form, and may include heating or cutting the metal, which can affect its strength.[13] Most brackets are milled from cold worked stainless steel, cast, or injection molded and sintered. One advantage of a milled product is that the strength is greater than a cast product of the same material because of prior cold working. Cracking may occur from milling or working a material. Surface cracks are more deleterious than internal defects because of the concentrated stresses at the surface of a loaded metal part. In the casting process, segregation can cause a nonuniform distribution of the alloy components in the final product. Gas holes occur when air is trapped in the casting, and act as stress concentrators, reducing the load a part can bear without failing. Hot tears are formed when a casting contracts to the point that a crack forms on the surface, and is usually in areas of design weakness such as the transition from one thickness to another as is found in orthodontic brackets. Inclusions can also be trapped in a casting, and can have varying negative effects depending on the material that is entrapped. These might include investment particles, metal oxides, or other insoluble materials.[14,15] Injection molding involves forcing a mixture of metal particles and an organic binder into a mold under high pressure. The product is then heated to slightly less than the melting temperature of the alloy to remove the organic matrix and bond the particles. The temperature control in this process is important to ensure removal of the matrix and complete bonding of the particles.

The choice of materials has also been influenced by patients demand for more esthetic appliances, leading to the use of plastic and ceramic brackets. While plastic has been shown to be too weak to satisfactorily transmit forces without deforming,[5,6] ceramic is used routinely now with good results and patient acceptance.[6-8] Stainless steel remains the most widely used material. In the past most brackets were made of an alloy of approximately eighteen percent chromium and eight percent nickel with the balance being mostly iron. The "300" series stainless steels are essentially variations of this basic composition, and possess excellent corrosion resistance, and good ability to be strengthened by cold working (Table 1). Presently, precipitation hardenable (PH) stainless steels are seeing increased usage in orthodontic brackets. One example is 17-4 PH stainless steel which can be strengthened by heat treatment and/or cold working. Precipitation hardening is the process of air cooling a product from 750°C to room temperature, and aging by reheating to 550°C for 90 minutes and cooling to room temperature. During aging, the copper precipitates in an uniform dispersion and disrupts the crystal lattice, requiring more force to cause plastic deformation. With a precipitation hardenable alloy, this process can be applied whether the product was milled, cast, or injection molded and sintered.

The purpose of this study was to examine mini twin metal brackets introduced since a similar study by Choi.[3] Bracket geometry, manufacturing methods, and material selection will be examined to determine their relation to force to permanently deform and stress at failure due to a torquing force. Failure was defined as the point of observable permanent deformation of the bracket (Figure 1).

MATERIALS AND METHODS

A. Test Design

Ten commercially available metal mini twin bracket types were tested to determine the force required to cause permanent deformation and the calculated stress at failure. Twenty brackets of each of the ten types were tested, for a total of 200 samples (Table 2).

Only maxillary right central incisor brackets of 0.018 X 0.025 inch slot size were tested to reduce variables between brackets. Three variables were tested to determine whether bracket geometry, manufacturing method, or material selection were related to the strength of this type of bracket.

A testing technique similar to that outlined by Flores was used to test the brackets with a torquing force (Figures 2,3,4).[7] A straight full size stainless steel archwire (Hi-T II 0.018 X 0.025 inch) was ligated with 0.010 inch stainless steel ligature wire into a bracket which was bonded to a steel ring. The steel base ring was held in a rigid vise which was affixed to an Instron Testing Machine. The brackets were oriented as they would be clinically with the incisal edge downward. A custom torquing key was engaged about the archwire on either side of the bracket, and held to it with a rubber band. Three inches from the depth of the bracket archwire slot (the end of the torquing key), a circular hole in the torquing key allows a wire to pass through until it is stopped by a round nylon ball stopper with a thin coat of silicone lubricant to allow nearly friction-free rotation during testing. The opposite end of the wire was fastened to the Instron load cell straight above the nylon ball (Figure 2,3,4).

B. Bracket Bonding and Ligation

The brackets were bonded around the outside circumference of a steel ring with a mesh grid machined into the surface. Before bonding, the rings were cleaned with acetone, and care was taken to avoid contaminating either the bracket base mesh or the steel rings. 3M Concise dental composite resin was used to bond the brackets to the rings, and each ring held 10 brackets, approximately 6 mm apart. Adhesive was separately mixed for each bracket and allowed to set a minimum of 24 hours. A straight stainless steel full size wire section was ligated tightly into the archwire slot of each bracket. The ligature wire was tightened with a Mathieu ligating plier in an attempt to equalize the force holding the rectangular wire into the bracket slots (Figure 4).

C. Testing of Brackets

The brackets were tested on an Instron machine after being mounted as previously described. The crosshead speed of the Instron was set at 1/2 inch per minute, and a computer generated a load/deformation curve. The point of permanent deformation was the point at which the slope of the load/deformation curve departed notably from the initial slope (Figure 1). All load values were converted to pounds for comparison purposes, and then stress at failure was calculated using a beam bending formula that was modified for metal orthodontic brackets (Appendix II). The gingival tie wing stem was measured because it was the portion of the bracket being loaded by the application of a lingual root torquing force. Bracket measurements were made with a Max·Cal electronic digital caliper (Fowler & NSK, $\pm$ 0.001 inch).

D. Statistical Method and Variables

The dependent variables for this study were the load force to permanently deform, and stress at failure calculated from load values. The independent variables were bracket geometry (vertical dimension, horizontal dimension, "a", and "c"- Appendix II), material selection (17-4 PH stainless steel, 303 stainless steel, and 316L stainless steel), manufacturing method (milled, cast, and injection molded and sintered), and bracket (ten groups- Table 2).*

ANOVA tests were run to determine if there were significant differences in each of the dependent variables due to material selection, manufacturing method, and bracket. Because not all combinations of the independent variables were commercially available, it was not possible to analyze the data as a factorial ANOVA. Therefore it was necessary to run a separate one-way ANOVA for each of the independent variables. Parametric one-way ANOVA was used to determine significance of difference for force to permanently deform. Due to problems with inequality of variance even after log transformation of data, the Kruskal-Wallis non-parametric ANOVA was used to determine significant differences in stress at failure.

Correlation coefficients were calculated for force to permanently deform and stress at failure and bracket geometry variables.

* Brackets donated by A-Co, American, GAC, Lancer, Orec, Ormco, RMO, TP, and Unitek.

RESULTS

Bracket descriptions including bracket geometry, manufacturing method, and material selection can be found in Table 2. While 200 brackets were tested, one bracket in group 3 debonded before a test value was obtained resulting in a sample size of 199 for statistical analysis. Table 3 contains means and standard deviations for the measured force to permanently deform and the calculated stress at failure for each bracket. Tables 4 and 5 contain means and standard deviations for force to permanently deform and stress at failure by material selection and manufacturing method respectively. Figures 5 and 6, respectively, show the mean forces to permanently deform and mean calculated stresses at failure by bracket type, along with an indication of material selection.

A. Force to Deform

In the ANOVA analyses with force to permanently deform as the dependent variable, the following results were obtained:

1) the brackets that were milled or cast did not have significantly different mean forces to deform, but had significantly higher means than brackets that were metal injection molded and sintered ($p < 0.0001$, Table 5);

2) of the brackets which were milled, brackets 1 and 2 had significantly lower mean forces to deform than brackets 5 and 6, which in turn had values lower than bracket 4 ($p<0.0001$, Table 3);

3) of the brackets that were cast, bracket 7 had a significantly lower value for force to deform than brackets 3 and 9 ($p<0.0001$, Table 3);

4) there was no significant difference in mean force to deform between brackets 8 and 10 which were both injection molded and sintered ($p=0.48$, Table 3);

5) mean force to deform for 316L stainless steel was significantly less than for 17-4 PH stainless steel, which was significantly less than the mean for 303 stainless steel ($p<0.0001$, Table 4);

6) of the brackets using 17-4 PH stainless steel, 4 of the brackets (1,2,8,10) had significantly lower mean force to deform values than the other 4 (3,5,6,9) ($p<0.0001$, Figure 4); and

7) the brackets fell into 3 significantly different groups based on mean force to permanently deform with bracket 7 having a mean significantly lower than brackets 10,8,1, and 2, which had means significantly lower than brackets 5,3,6,9, and 4 ($p<0.0001$, Table 5).

Correlation coefficients for force to deform and bracket geometry variables are given in Table 6. The highest correlation was found between force to deform and the measured value "a" (Appendix II) with 33% of the variability in force to deform explained by differences in "a" (R^2=0.33, $p<0.0001$).

B. Stress at Failure

The Kruskal-Wallis ANOVA with stress at failure as the dependent variable showed that:

1) the manufacturing methods were all found to be significantly different, with casting having the lowest mean, followed by milling, with injection molding and sintering having the highest mean stress at failure ($p\leq0.001$, Table 5);

2) 17-4 PH stainless steel and 303 stainless steel were not significantly different, but had a significantly higher mean stress at failure than 316L stainless steel ($p<0.0001$, Table 4);

3) two bracket groups were not significantly different from each other (2 and 3) with mean stress at failure significantly lower than all other brackets except 7, which was the lowest ($p<0.0001$). The remaining brackets in increasing order of mean stress at failure were 1,9,10,4,5,6,and 8.

Correlation coefficients for stress at failure and bracket geometry variables are given in Table 5. The highest correlation was found between stress at failure and the measured value "c" (Appendix II) with 45% of the variability in stress at failure explained by the value "c" (R^2=0.045, $P<0.0001$).

DISCUSSION

Significant differences were found between manufacturing methods when evaluating force to deform, with the value for metal injection molded and sintered below the values for cast and milled, with the latter two not significantly different from each other. This is in contrast to the results of stress to deform, with metal injection molding having the highest value, followed by milling, then casting. In theory, the value for stress should be a measure of the materials' characteristics, but the results of this study indicated that there were differences in the same material from one manufacturer to another. Since the formula for stress includes dimensions of the wings about the archwire slot, this difference may be explained by a differences in design which gives a bracket a high stress at failure when taking into account its thin tie wing stem, but ultimately weak when tested for force to deform without consideration of tie wing stem measurements. It is also possible that some design features or alteration of the metal by the manufacturing methods are not accounted for by the formula for stress. These alterations could include cracks, segregation, gas holes, hot tears, inclusions, improper heating and annealing, or cold working. Some of these various alterations can be beneficial at times, as well as a detrimental at other times, depending on the material and the intended application of the product. Since many of the manufacturing methods are proprietary, accurate research in this area is more difficult, and the factor of metal alteration is unknown.

Significant differences were found between all three different materials used by the manufacturers of brackets in this study. The mean values for 17-4 PH stainless steel and 303 stainless steel tested in this study were well within the published range for their stress to yield, but the 316L was well below the expected value.[16] This discrepancy may be explained by closer examination of the modified beam bending formula used in this study. The value "a" is a combined measure of the mesial-distal width of each tie wing of the bracket. This measurement is accurate for a standard shape of twin bracket, or for a single tie wing bracket, but becomes problematic when the bracket wing is of an unusual shape as in groups #7 or 10 (figures 9 and 10). Number 7 is the 316L stainless steel group and has the tie wings connected together, so the "a" measurement was taken to include the entire mesial-distal dimension. This is an inaccurate measurement due to the varying thickness of the connecting area, and since "a" is in the denominator of the equation for stress, a larger value reduces the value for stress at failure. In spite of this problem, the value for force for 316L stainless steel supported the idea that it was the weakest of the three metals tested. The 17-4 PH stainless steel was the material that withstood the highest value for force to deform, though not significantly different from 303 stainless steel for stress to fail. Thus, it is not surprising that 17-4 PH stainless steel was the material used in eight of ten brackets in this study. It should be pointed out, however, that 17-4 PH stainless steel can have a range of values of tensile strength before being put through the manufacturing process for an orthodontic bracket.[16] This material was not intentionally selected for this study, but is simply a representation of the brackets being offered by the major manufacturers of orthodontic appliances today.

This study did not demonstrate a useful correlation between the variables vertical and horizontal dimension and the variables force to deform and stress at failure (Table 5). This may be explained by the fact that all the brackets in this study were considered to be mini twin brackets and the vertical dimensions varied by a maximum of only 12%, whereas regular twin brackets are about 30% larger than mini twins. Therefore, the lack of significance may be due to a minimal difference in the size of the brackets tested. There were, however, useful correlations with the measurements "a" and "c" (Appendix II). The values for "a" explained approximately 34% of the variability in the force to deform, but only approximately 19% of the variability in stress at failure. The values for "c" only explained approximately 14% of the variability of force to deform, but explained approximately 45% of the variability in the stress at failure. Thus "a" was more closely correlated with the force to deform, while "c" was more closely correlated with the stress at failure; "a" values changed inversely to the force and "c" values increased with the force. Values for "a" and "c" changed inversely to stress at failure. While this relationship for "c" is more easily predicted due to its appearance in the formula for stress as "c^2" in the denominator, the relationship of "a" to force to deform is not as expected. This may be due to two brackets in this study which are not of a standard mini twin design, brackets number 7 and 10 (Figure 9 and 10). Each of these brackets has a connection between the tie wings, and though it is not a full thickness, it still may contribute error in the calculation of stress at failure and the correlation of "a" with force to deform for these two brackets.

The divergent results in relation to the amount of force and stress to deform and the materials tested validate the requirement for having these two different tests. For the bracket designer and manufacturer stress values are practical in guiding future designs, and finding areas of improvement. For the clinician, the force to deform is a more practical measure of what the bracket can do when a force is put to it, relative to another bracket.

When comparing the mini twin brackets in this study to those tested by Choi, the range of values for force to deform were similar (0.127 - 0.247 pounds previously compared to 0.168 - 0.243 pounds for this study), while the mean increased from 0.174 pounds to 0.212 pounds.[3] Of particular interest is that the mini twin brackets in this study had a mean force to deform (0.212 pounds) that is not only greater than the previously reported value for mini twin brackets (0.174 pounds), but is also greater than the previously reported mean value for all the brackets in that study (also 0.174 pounds), including regular twin brackets (0.203 pounds). This is probably due to a greater number of 316L stainless steel rather than 17-4 PH stainless steel in the selection of brackets in the previous study, since the mean value for brackets of 17-4 PH stainless steel in this study (0.214 pounds) did not vary greatly from the previously reported mean for 17-4 PH stainless steel (0.200 pounds).[3]

It should also be noted that the preponderance of 17-4 PH stainless steel brackets in this study influence the result by averaging the various other factors, while the two other materials come from just one group each, and are disproportionately influenced by design and any unknown factor in the manufacturing process.[3]

It does not appear that there is any decrease in the strength of currently avalilable mini twin brackets. Choi did not provide the dimensions of each bracket in his study, so direct comparisons are not possible.

To truly test the individual contribution of bracket geometry, manufacturing method, and material, brackets of like design, made in each material and made by each different method would need to be tested. Also, a series of varied sizes following the above variables should be tested. A study of this design would allow the use of factorial analyses and better delineate the trends.

SUMMARY & CONCLUSIONS

Ten types of mini twin brackets were tested for the force required to deform them, and stress values were calculated using a modified beam bending formula.

Statistical analyses (ANOVA) revealed significant differences in manufacturing methods and materials. Milling proved superior for force to deform, while injection molding and sintering withstood the highest stress at failure. 17-4 PH stainless steel withstood the highest force to deform and stress at failure. A correlation with the overall size of the bracket was not found, though there was a limited variation in size. Significant correlations between the size of the tie wing stem and force to deform and stress at failure were found.

It appears that the strength of a bracket is multifactorial and the factors are not easily separated. If a bracket is to be chosen for its strength characteristics, it must be tested on an individual basis to determine how it compares to other similar brackets.

Currently available mini twin brackets are as strong as regular twin brackets tested by Choi[3], due to more use of the stronger 17-4 PH stainless steel.

APPENDIX I

Table 1
Nominal Composition of Alloys[16]

Alloy	% Cr	% Ni	% Mo	% Cu	% Fe
303	18	8	0	0	balance
316	17	12	2.5	0	balance
17-4 PH	17	4	0	4	balance

Table 2

Bracket Description

ID#	# Tested	Material	Mfg.** Method	Vert.* Dim.	Hor.* Dim.	"a"*†	"c"*†
1	20	17-4 PH	M	0.115	0.142	0.072	0.025
2	20	17-4 PH	M	0.123	0.138	0.080	0.025
3	19	17-4 PH	C	0.126	0.166	0.090	0.025
4	20	303	M	0.130	0.143	0.064	0.025
5	20	17-4 PH	M	0.118	0.160	0.070	0.020
6	20	17-4 PH	M	0.120	0.142	0.066	0.020
7	20	316	C	0.122	0.144	0.144	0.020
8	20	17-4 PH	IMS	0.120	0.139	0.066	0.015
9	20	17-4 PH	C	0.124	0.137	0.068	0.025
10	20	17-4 PH	IMS	0.124	0.139	0.120	0.015

* *Dimension in inches*
** *M = milled*
C = cast
IMS = injection molded and sintered
† *See Appendix II*

Table 3

Force and Stress at Failure

	Force*		Stress**	
ID#	Mean	S.D.	Mean	S.D.
1	0.197	0.019	79,000	7,800
2	0.202	0.016	73,000	5,600
3	0.231	0.017	74,000	5,600
4	0.243	0.024	109,000	10,700
5	0.228	0.015	147,000	9,800
6	0.231	0.014	158,000	9,900
7	0.168	0.016	52,000	4,900
8	0.196	0.016	237,000	19,100
9	0.236	0.016	100,000	6,700
10	0.191	0.023	128,000	15,600

* *Force in pounds*
** *Stress in pounds/square inch*

Table 4

Effect of Material on Force to Deform and Stress at Failure

Material	Number Tested	Force*		Stress**	
		Mean	S.D.	Mean	S.D.
17-4 PH	159	0.214	0.025	125,000	54,000
303	20	0.243	0.024	109,000	10,000
316L	20	0.168	0.016	52,000	5,000

* *Force in pounds*
** *Stress in pounds/square inch*

Table 5

Effect of Manufacturing Method on Force to Deform and Stress at Failure

Mfg.* Method	Number Tested	Force**		Stress†	
		Mean	S.D.	Mean	S.D.
M	100	0.220	0.025	113,000	36,000
C	59	0.212	0.035	75,000	20,000
IMS	40	0.194	0.020	182,000	58,000

* *M = milled*
** *C = cast*
† *IMS = injection molded and sintered*

Table 6

Multiple Correlation Coefficents Between Dependent Variables and Bracket Geometry Variables

	"a"	"c"	Vert. & Hor. Dimension
Force to Deform	0.58**	0.37**	0.39**
Stress at Failure	0.44**	0.67**	0.26*

* *p = 0.001*
** *p = 0.0001*

Figure 1. Example of Load/Deformation Curve and Estimation of Point of Failure

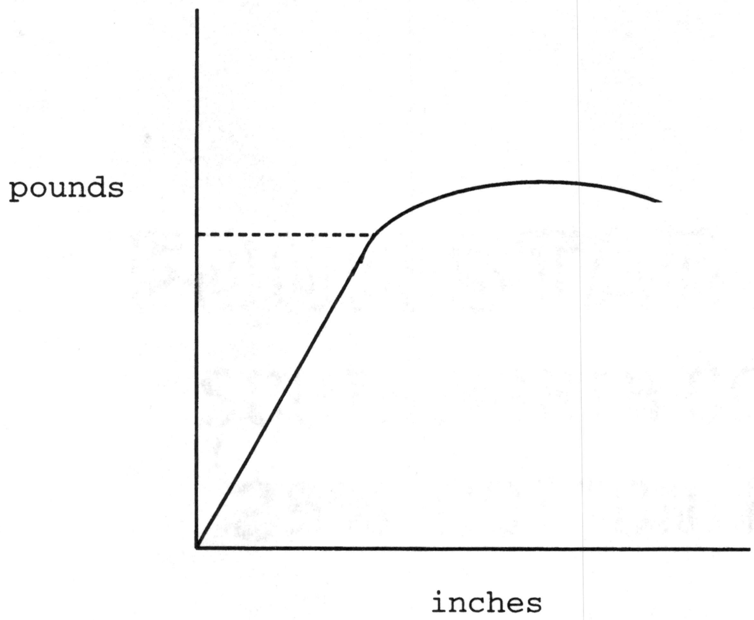


Figure 2. Bracket Testing Apparatus

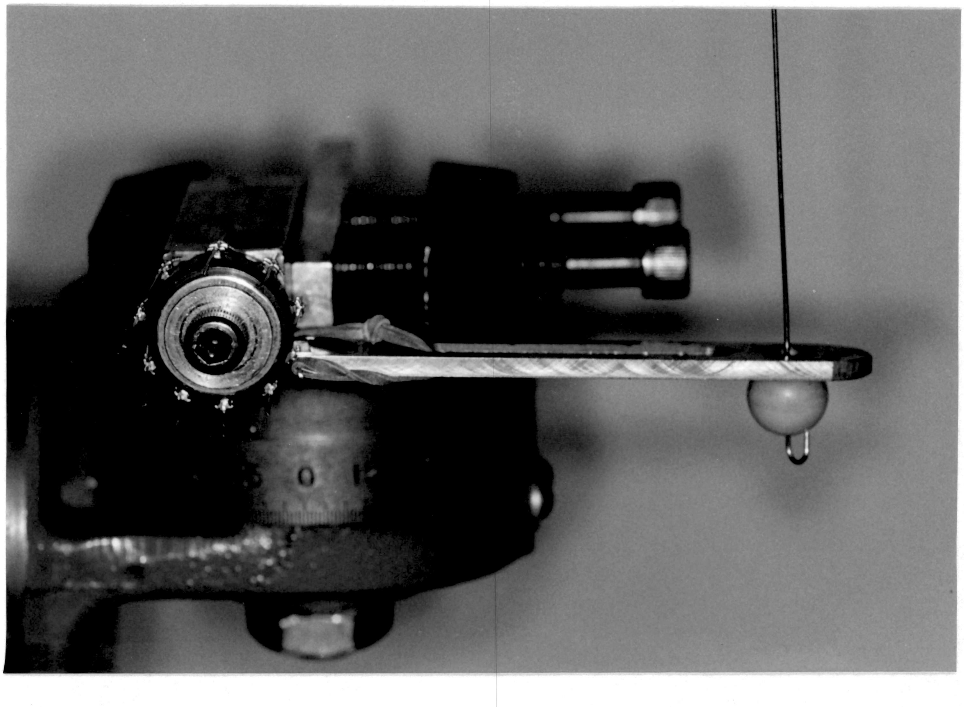


Figure 3. Attachment to Instron Machine

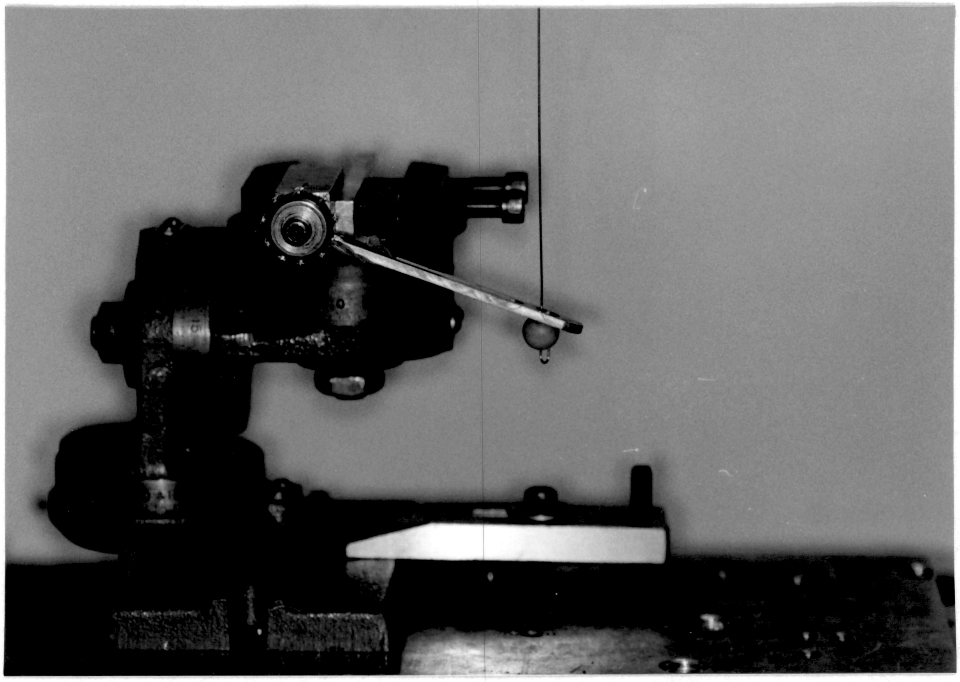


Figure 4. Archwire Ligated into Bracket Slot

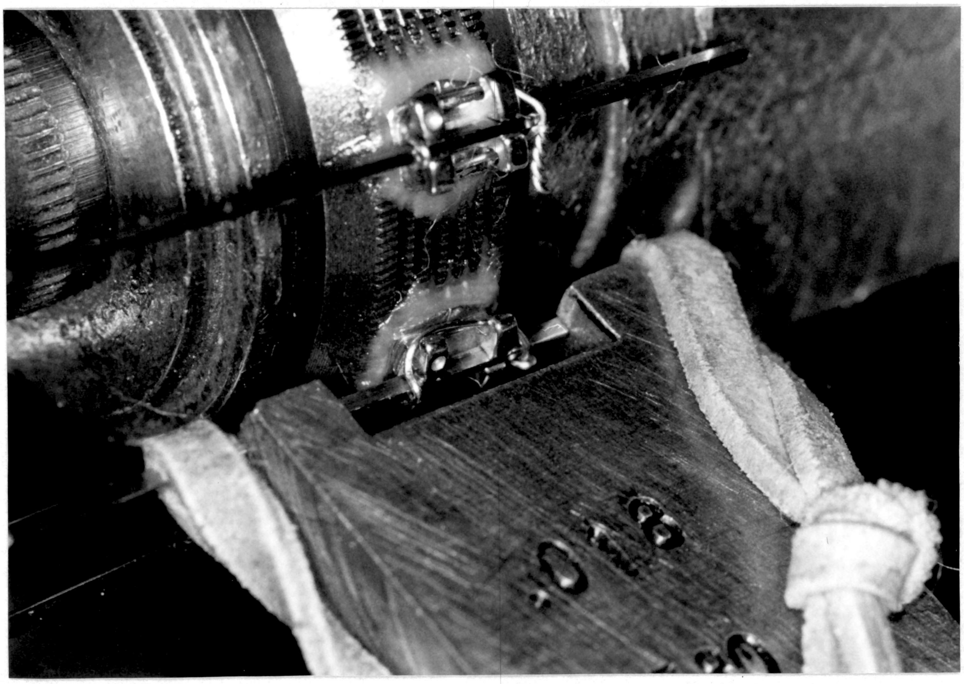
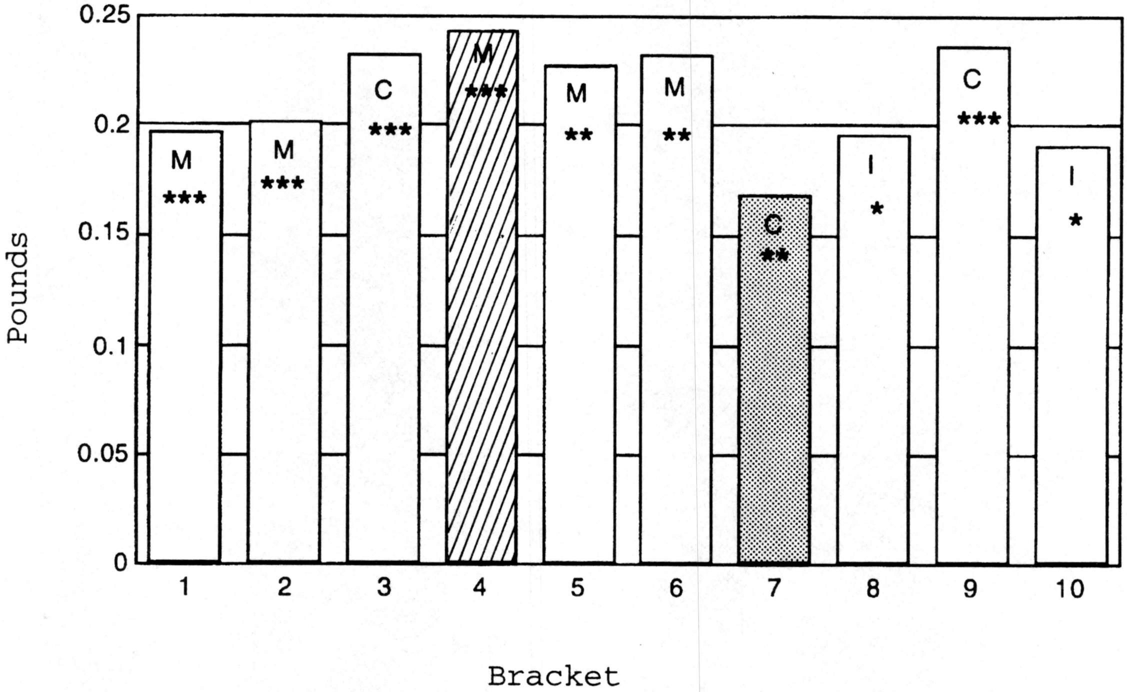


Figure 5. Mean Force to Deform Brackets.



17-4 PH SS

303 SS

316L SS

* "C"=0.015 inch

** "C"=0.020 inch

*** "C"=0.025 inch

M = Milled

C = Cast

I = Injection Molded and Sintered

Figure 6. Mean Stress at Failure.

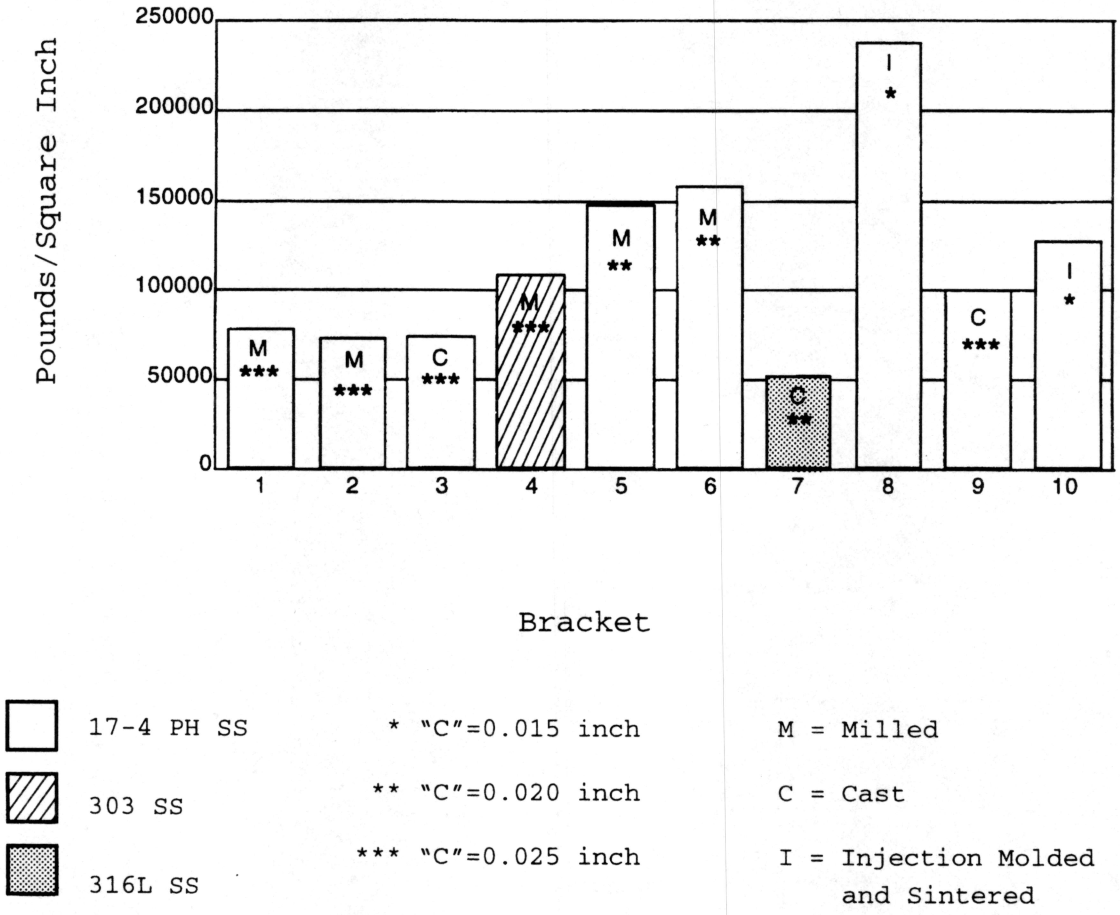


Figure 7. Anterior View of Brackets 1 and 2.

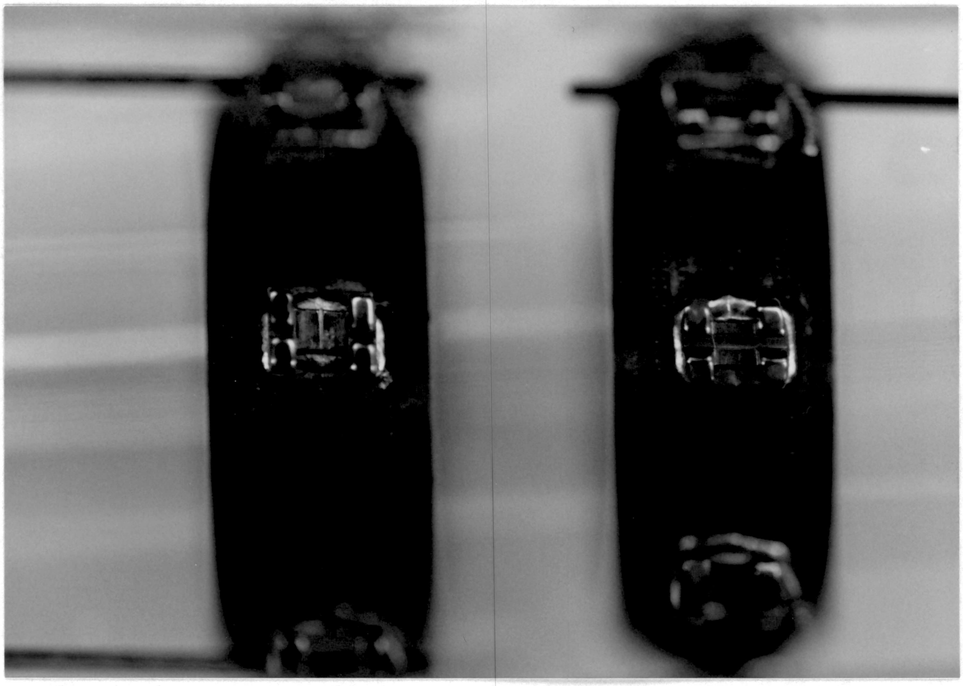


Figure 8. Anterior View of Brackets 3 and 4.

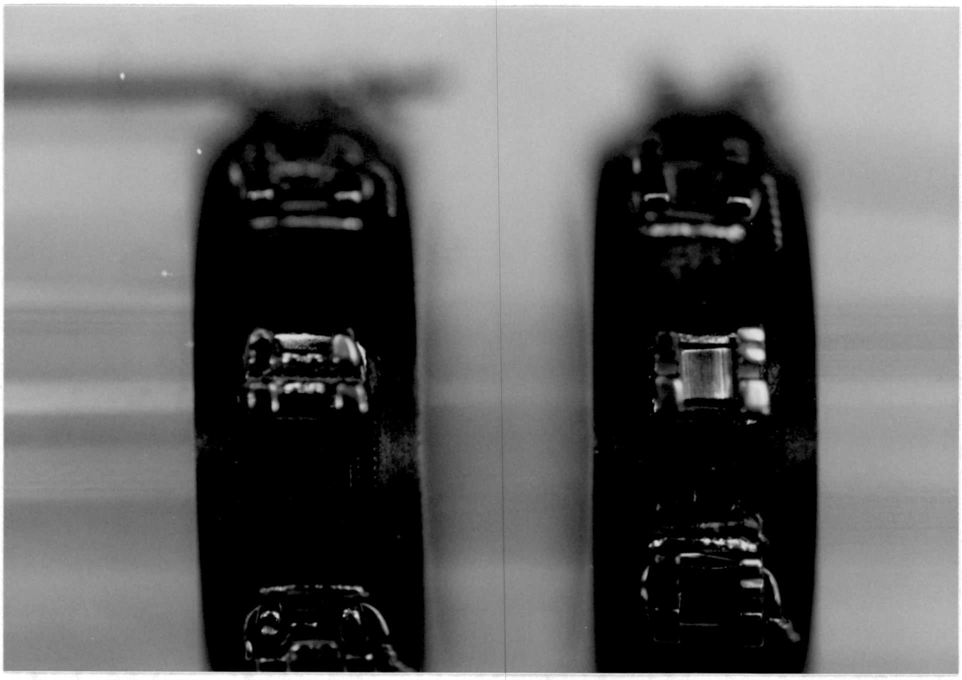


Figure 9. Anterior View of Brackets 5 and 6.

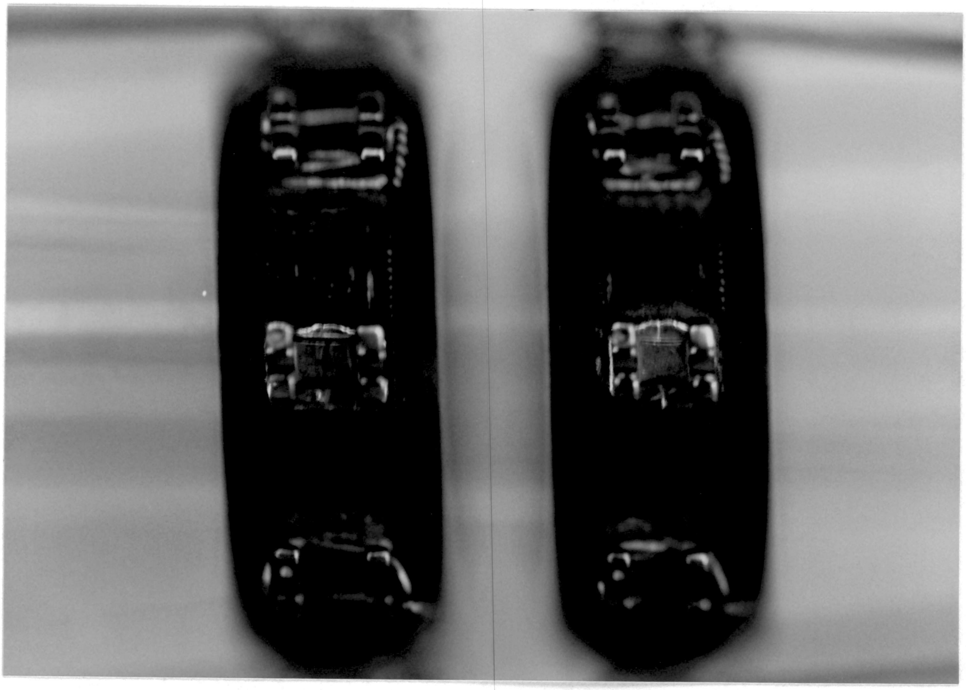


Figure 10. Anterior View of Brackets 7 and 8.

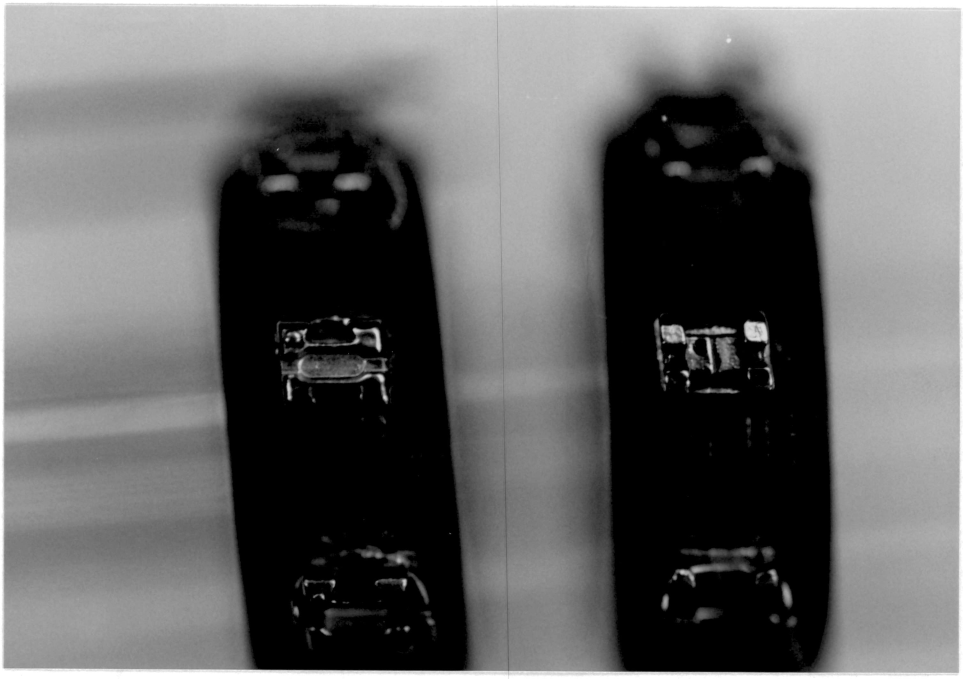
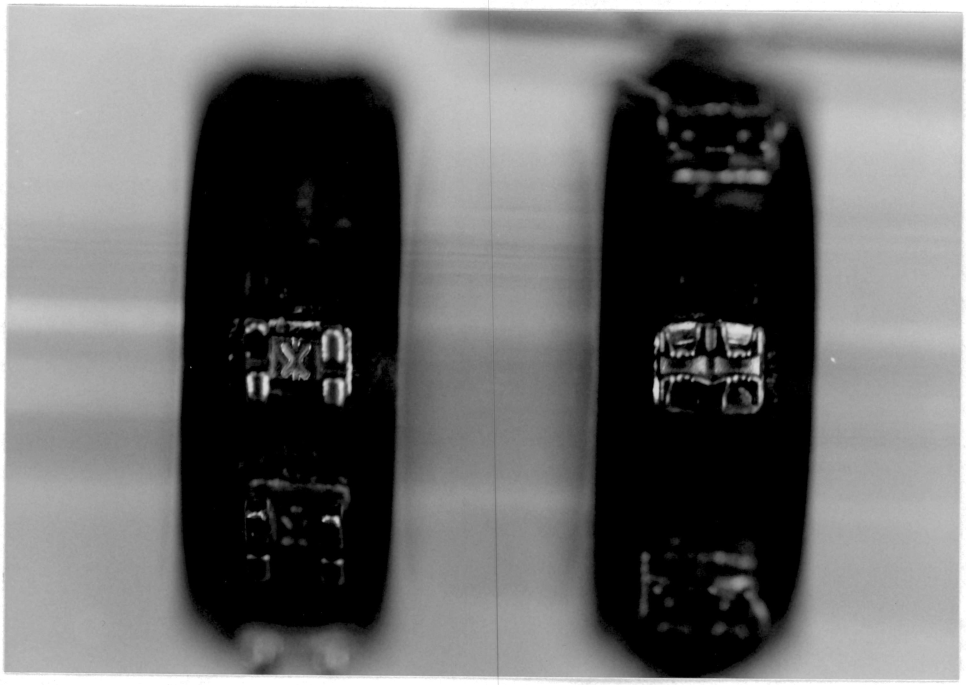


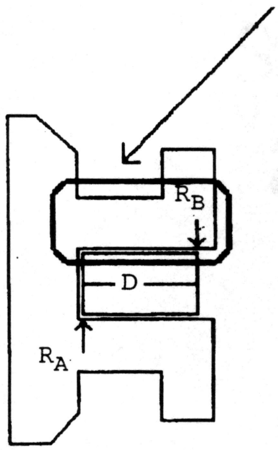
Figure 11. Anterior View of Brackets 9 and 10.

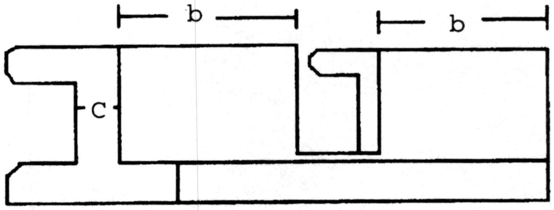


APPENDIX II

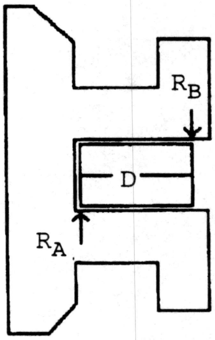
The following illustrations will be referred to in the demonstration of the derivation of the modified beam bending formula used for calculation of stress at failure of mini twin orthodontic brackets:

This portion of the bracket viewed as a beam.





The width of the archwire, "D", is a constant in this experiment, and defines the point of resistance to the "beam", points R_A and R_B.



In the testing of the brackets with a torquing force, a lever arm (torquing key) is used that is three inches long, referred to as length "L". For the points of resistance and force applied (P) to the lever arm, the sum of the moments is equal to zero, allowing solving for the expression R_B;

$$0 \times R_A - D \times R_B + LP = 0$$

and

$$R_B = \frac{LP}{D}$$

The formula for stress at failure was adopted from Flores, et. al., equation 3:[7,17]

$$S = \frac{M\ C'}{I}$$

where

$$M = R_B D$$

$$C' = \frac{C}{2}$$

$$I = \frac{1}{12} ac^3$$

Substituting the above values into the equation, and the constant values D = 0.025 inches and L = 3 inches, the following formula for stress at failure is obtained:

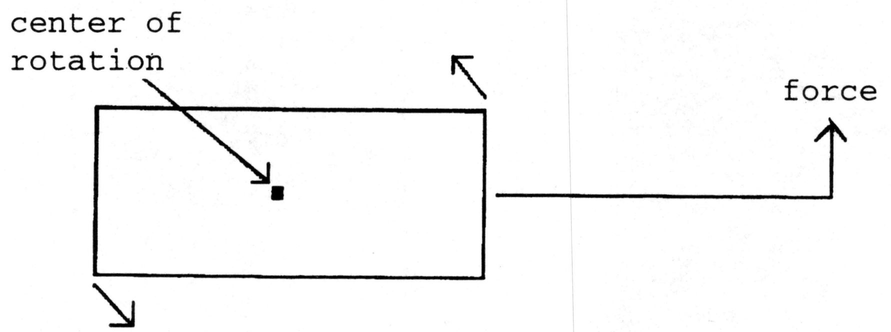
$$S_F = \frac{18\ P}{ac^2}$$

where P = applied force at failure
a = measured mesial-distal width of tie wings b + b
c = occlusal-gingival thickness of tie wing stem

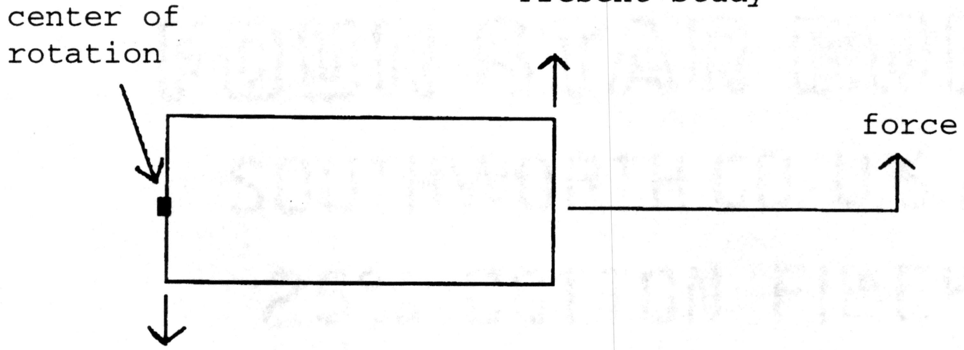
Because of the constants in this formula, the above form is only valid for the conditions of this experiment.

The simplification of the formula from the one used by Flores[7], is due to the assumption that the archwire acts as a rigid lever against the bracket wing, rather than rotating in the slot as was assumed before.

Previous study



Present study



It is felt by the authors that this new view of the behavior of the archwire is a more accurate representation of what is happening in testing.

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