AN EVALUATION OF WIRES FOR ORTHODONTIC
LINGUAL EXPANSION ARCHES

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CHAPTER 1

1. INTRODUCTION AND HISTORY

The purpose of this research is to compare the mechanical properties, spring rate and proof load, of a nickel base alloy wire - Nimonic 90, with the following materials

(1) Stainless Steel Wire

(2) Cobalt Chromium Wire

(3) Platinised Gold Wire

when bent in a structural form similar to that of the upper lingual expansion arch, and to consider which of these materials is the most suitable for this type of orthodontic appliance.

Anderson [1] in his textbook "Practical Orthodontics" attributes to Pierre Fauchard in 1723 the idea of the orthodontic expansion arch, and gives the history and development of several types of expansion appliances; such as those of:-

(a) Westcott, (1859) who used a double clasp on either side of the dental arch and a wire across the palate for lateral expansion.

(b) Farrar, who classed a number of appliances as "jacks", some of which were only used for moving teeth that were inclined towards one another, and depended on this inclination for retention of the appliance, and others which were anchored in various ways by making use of the elasticity of metal, screws, ligatures, clasps or bands.

(c) W.H. Coffin, who in 1881 introduced the coffin plate, which consisted of a divided vulcanite plate, the two halves being connected by a piece of piano wire bent to the shape of the letter W. The appliance was held in place by either caps or clasps on the molars and by means of the spring in the wire, exerted lateral pressure, or expansion force.

(d) V.H. Jackson who developed a system of appliances which combined an improved "crib" with a modification of the W-shaped wire as used by Coffin.

The lingual, or butterfly lingual expansion arch in use today normally consists of a wire bent to a W shape attached to orthodontic bands in the molar or pre-molar region. Some examples of this type of appliance are given in Figures (i), (ii), (iii), (iv). (1).

The appliance is activated by expanding the arch form beyond its proportional limit and it is then inserted under compression resulting in a lateral expansive force.

The W-shaped spring is normally attached to the orthodontic bands by silver soldering, although other methods of attachment are occasionally used, e.g. the wire can be bent so that it fits into a slot on the lingual of the band and the spring can then be removed without dislodging the bands. However the soldered appliance is normally used; it is easier to fabricate

Figure 1. (i)

Upper Lingual Expansion Arch

Figure 1. (ii)

Upper Lingual Expansion Arch

Figure 1. (iii)

Upper Lingual Expansion Arch

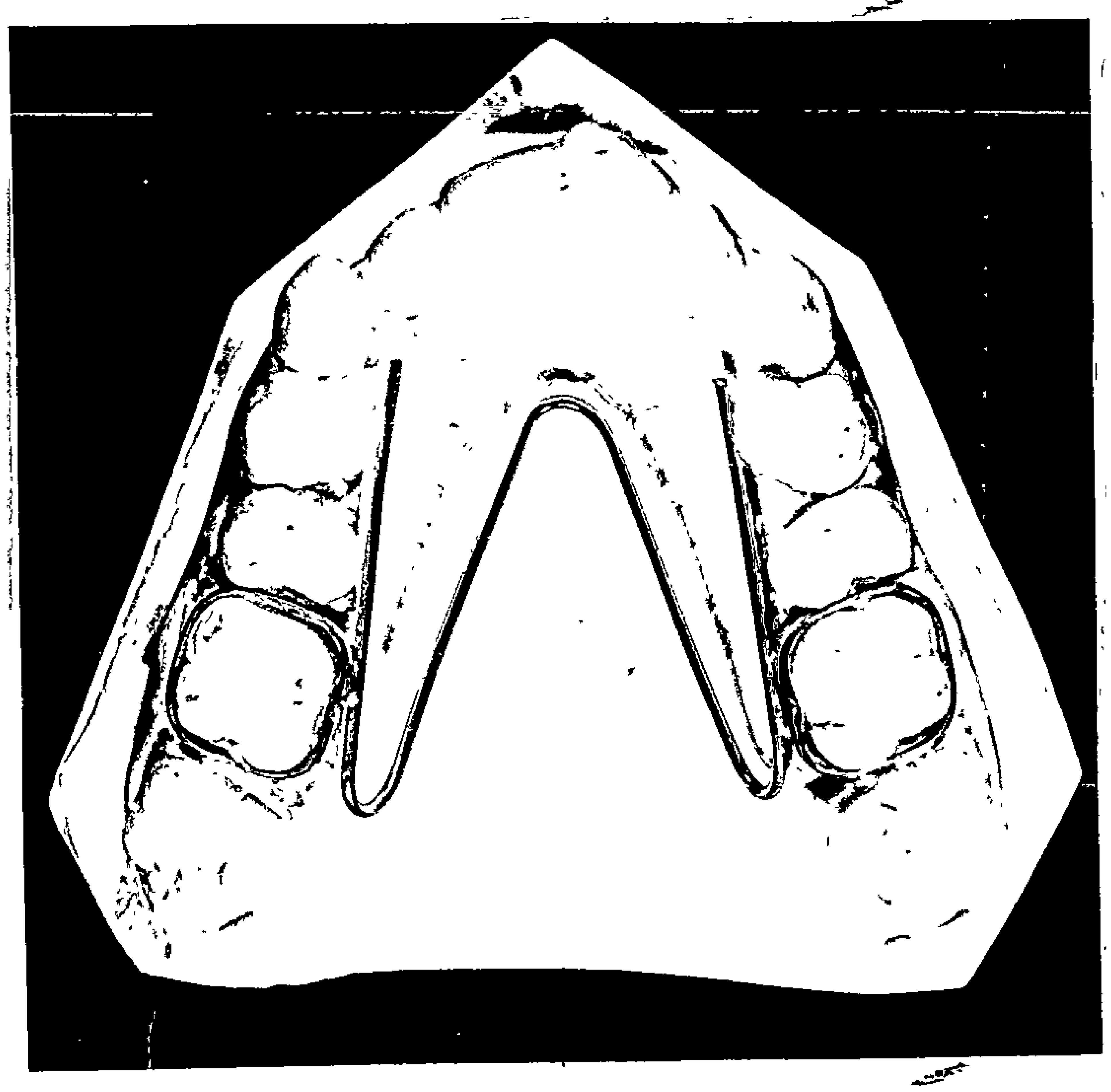


Figure 1. (iv)

Upper Lingual Expansion Arch

and appears to offer greater directional control of the lateral forces exerted by the appliance. Wires of platinised gold, stainless steel and more recently cobalt chromium, are usually used for the W spring of this appliance.

Wires of various alloys have been used for the W springs of expansion arches, and since the introduction of stainless steel wire to orthodontics, around 1930, (Gaston)[25] many comparisons have been made between precious metal and stainless steel for orthodontic purposes.

The early expansion appliances usually used a spring of piano wire, as in the Coffin Plate (Anderson)[1] or a precious metal alloy spring, (Pollock[41], Eby[23]). H.C. Pollock[41] advocated the use of gold plated tungsten wire, as, "the elastic content of tungsten being about twice that of platinum, its stiffness about six times that of 30% iridium in platinum, also the quality that it does not anneal or lose its stiffness and elasticity at tremendous heat, makes it particularly adaptable for some of the uses of the orthodontist". The chief objections, then, to this wire were its brittleness "it had to be cut or etched with a knife - edged stone and then broken like glass - and its unreliability in large sizes".

Dewey (1923)[21] advocated the use of spring gold and platinum wire for removable orthodontic appliances "as it is a desirable material from which to obtain spring force".

Williams (1923)[69] compared various gold wires using piano wire as a standard and attempted to translate the desirable orthodontic properties of wires into actual tangible figures of strain or stress. He designed an instrument to determine the suitability or not of orthodontic wires which was based on the "elasticity" of the material tested.

Brumfield (1930)[11] gave an interpretation of the desirable properties of finished orthodontic structures from the published test results of individual gold alloys. He calculated values of load and deformation of various auxilliary springs of gold wires.

De Coster (1932)[18] began using stainless steel in orthodontics in 1924. He advocated stainless steel for bands, auxilliaries and arches, and felt that great progress in the use of rustless steel was made by the use of electric welding.

Simon (1933)[51] used rustless steel for his lingual spring beam apparatus and considered that "very probably rustless steel will be the material of the future".

Paffenbarger et al (1943)[40] credit Frederich Hauptmeyer, chief of the Krupp Dental Clinic in Essen, Germany, as the first user of stainless steel for oral appliances. They felt that stainless steel compared very favourably with gold alloy wires as an orthodontic spring material. However gold had one definite advantage in that it could be hardened by heat treatment after appliance construction.

Angell (1950)[3] compared 18 - 8 stainless steel wire with platinised gold wire, using tensile and bend tests, for orthodontic arches and springs and concluded that "gold alloy wires will serve orthodontists for arches and springs better than the best stainless steel wires. The advantages of gold alloys which can be heat treated after soldering is especially pronounced as compared with stainless steel".

Steiner (1953)[56] considered the physical qualities of stainless steel and precious metal and concluded that while both have advantages and are useful for orthodontic purposes, precious metal is the most suitable for orthodontic purposes.

Gerber (1964)[26] described a butterfly expansion appliance in which he used a spring of cobalt chromium (Blue Elgiloy) wire.

Craig et al (1965)[16] compared 17 - 7 precipitation - hardenable stainless steel, with 18 - 8 stainless steel and cobalt nickel wires used in orthodontics, and concluded that while the properties of the 17 - 7 precipitation hardenable stainless steel in the cold worked martensitic condition were comparable to those of the 18 - 8 stainless steel and cobalt chromium nickel wires examined, the material had no significant advantages over 18 - 8 stainless steel for orthodontic use.

Mahler and Goodwin (1967)[33] compared elastic deformation - force ratios and elastic force limits of small diameter orthodontic wires of stainless steel and cobalt chromium from different manufacturers when bent into loops of various configurations. They gave no details of wire diameters and wire configurations were bent with pliers. They concluded that of the types, designs, and conditions tested all produced elastic force limits in excess of that apparently required of the light wire applications and that heat treatment increased the elastic force limit appreciably in most cases but decreases slightly the elastic deformation - force ratio.

Howe et al (1968)[29] compared the effects of stress relief for types 302 and 316 austenitic stainless steel orthodontic wires. They found sizeable variations in mechanical properties from batch to batch of the same wire of the same grade. They concluded that the type 316 material examined exhibited superior elastic properties compared to the type 302, but that both types needed a stress relief anneal to give maximum stiffness and resistance to deformation.

The reason for suggesting that the nickel-base alloy chosen (Nimonic 90) may be suitable for this type of appliance are:-

(a) As supplied in wire form the alloy is relatively ductile and appliances should be able to be constructed quickly and accurately.

(b) The alloy has a high ultimate tensile strength and proportional limit after hardening.

(c) The alloy can be aged over a wide range of temperatures, 300° - 800° C, without seriously affecting its mechanical properties.

The materials used for comparison were (nominal diameter 0.036 in.)

1. Platinised Gold wire (Ney Oro - Elastic 12)
2. Stainless Steel wire (Remanit Dentaurum)
3. Cobalt Chromium Alloy wire (Elgiloy Yellow)
   (Elgiloy Blue)

The reasons for selecting these wires for comparison were:-

1. <u>PLATINISED GOLD WIRE</u>

(a) It is often used for this appliance.

(b) It has a low modulus of elasticity compared with stainless steel.

(c) It has a high proportional limit after ageing (for a precious metal alloy).

(d) It can be age hardened after fabrication of appliances and the process is reversible and repeatable.

2. <u>STAINLESS STEEL WIRE</u>

Stainless steel wire is widely used in orthodontics and is used for this appliance. The proportional limit can be increased by work hardening and heat treatment.

3. <u>CHROMIUM COBALT WIRE</u>

(a) It is recommended and widely used for this type of appliance.

(b) It can be heat treated after fabrication of appliance. Two forms of this wire were used for comparative purposes, these were Yellow Elgiloy - designated cobalt chromium Y and Blue Elgiloy - designated cobalt chromium B. The distributor(44) describes Yellow Elgiloy as being ductile, and Blue Elgiloy as being soft.

The upper lingual expansion arch uses the elastic properties of wire to deliver the forces derived from the appliance.

To present the theoretical principles involved it is necessary to consider

(a) The Elasticity and Strength of Materials ..... Chapter 2

(b) Structural Interpretation of Physical Properties of Materials .... Chapter 3

(c) Mechanical Springs .... Chapter 4

All definitions unless specifically stated otherwise are taken from Metals Handbook 8th Edition.(34)

CHAPTER 2

2. ELASTICITY AND STRENGTH OF MATERIALS

2.1. STRESS, STRAIN AND ELASTICITY (SALMON)[45]

2.1.1. ELASTIC MATERIAL. When making an analytical study of the effect on a body of distorting forces, it is customary to assume that the material of which the body is composed is perfectly elastic. That is to say, it is assumed that not only do all effects of the distorting forces immediately disappear on removal of those forces, but that the distortion produced in the material is proportional to the magnitude of the effort which gives rise to it. It is further assumed that the material has the same elastic properties in every direction. Such material is called isotropic material. No engineering material completely satisfied this ideal, but many approximate closely if the distortion produced be not too great. The theory given below can be safely applied to these materials provided that the stress produced at any point does not exceed the elastic limit. This limit is discussed in 2.1.5.

2.1.2. TENSILE STRESS AND STRAIN. Suppose that a bar of length l be subjected to two longitudinal forces F F, directed along its axis, as shown at (i) Figure (2). Careful measurements will show that, as a result, the bar has lengthened by a certain amount, which will be denoted by δl. This alteration in length δl is called the extension produced by the forces F F.

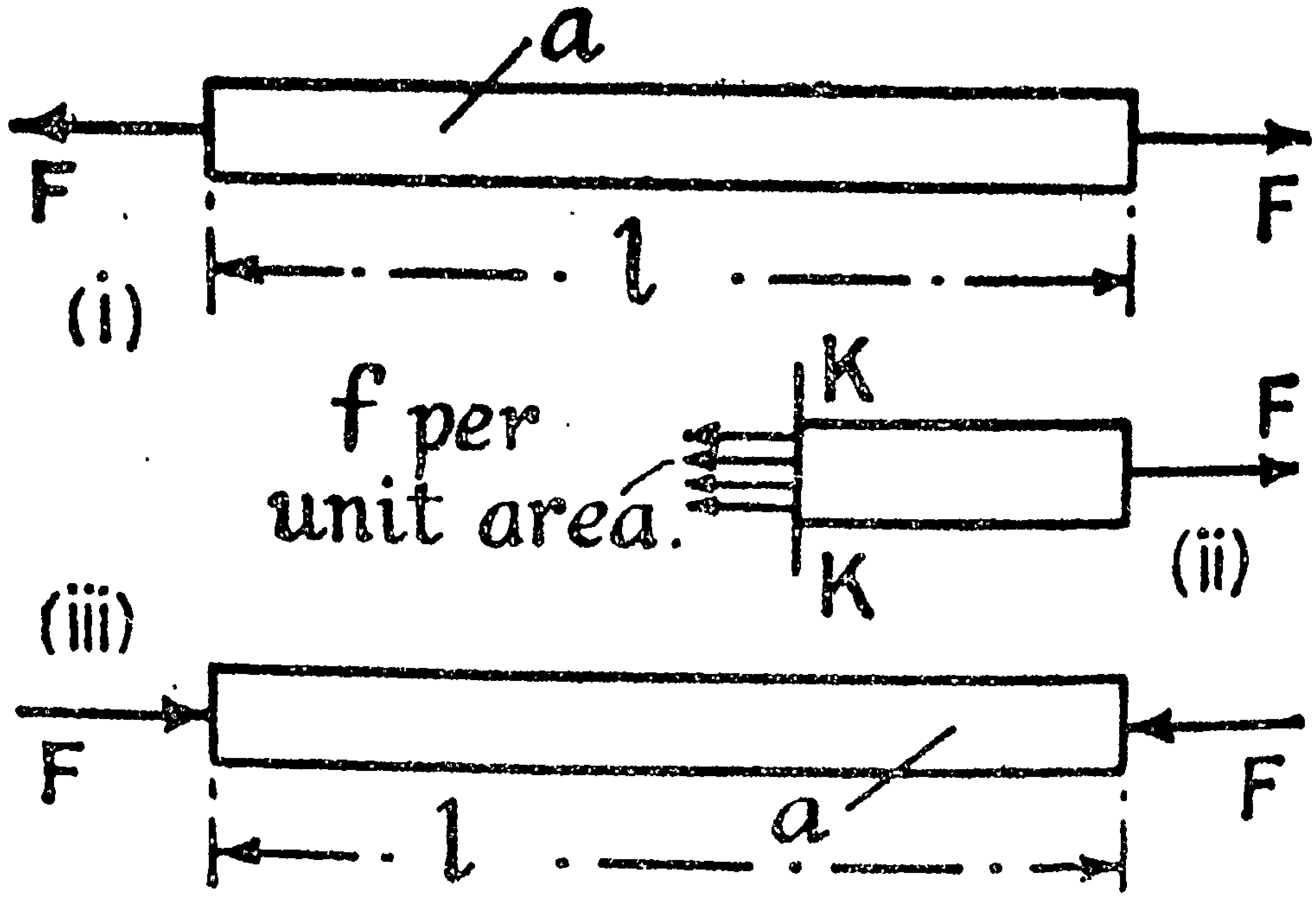


Figure 2. Forces on a Longitudinal Bar.

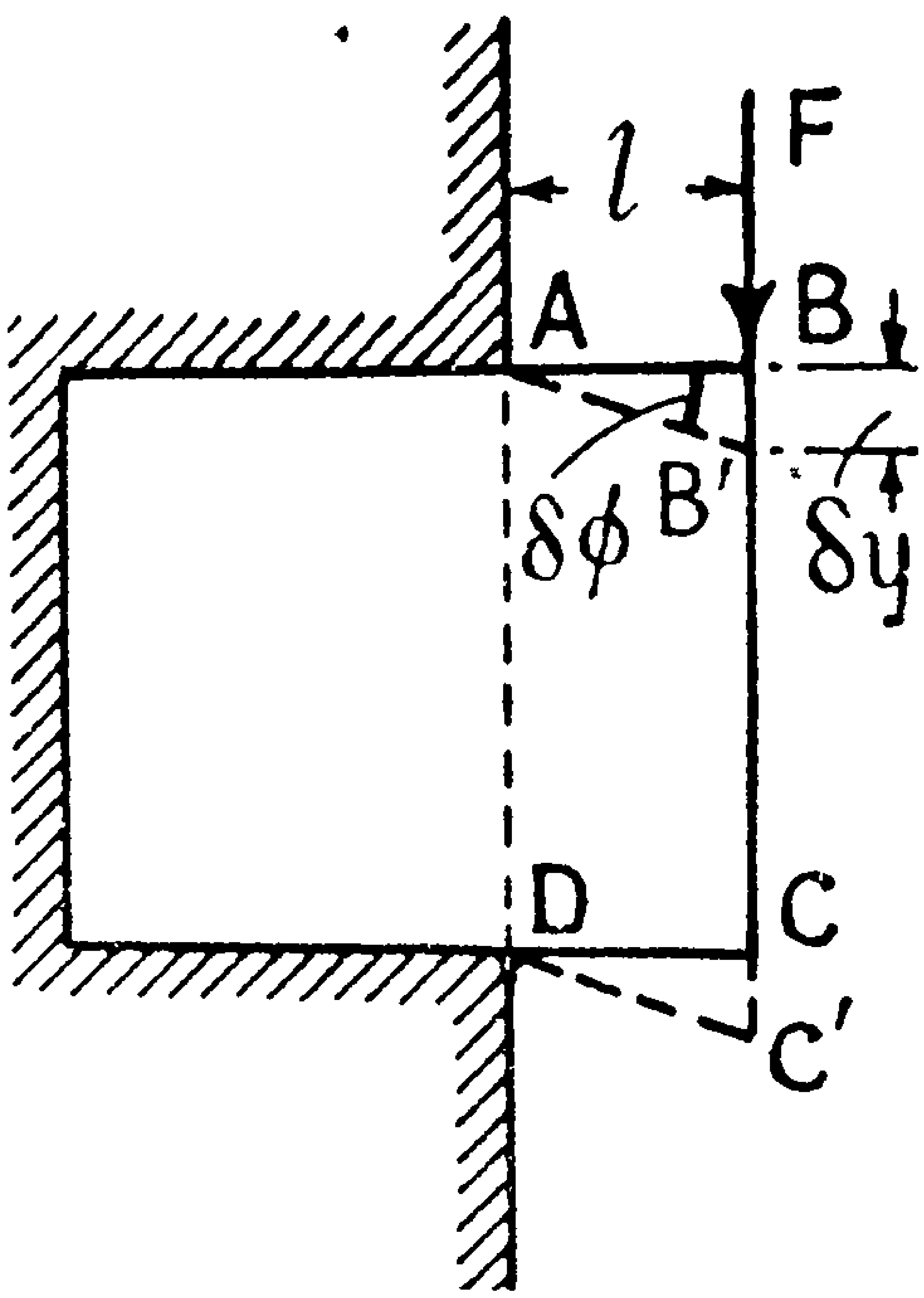


Figure 3. Shear Forces on a Rigid Bar.

The ratio $\dfrac{\text{extension}}{\text{original length}} = \dfrac{\delta l}{l} = S$ .... (1)

is termed the strain. Evidently the strain is the alteration of length per unit length of the bar, for if $l = 1$, $S = \delta l$. Owing to the action of the external forces F F, internal molecular forces, or stresses, will be set up in the material of the bar; and at any cross - section such as K K (ii, Figure 2), if the area be a and the intensity of molecular force or stress produced be f per unit area, it is evident that for equilibrium

$F = a f$; or $f = \dfrac{F}{a}$ .... (2)

By the expression stress, therefore, is to be understood the intensity of internal force called into play by the external forces. This intensity is expressed as units of force per unit of area. Since, in the example under consideration, the chief deformation produced is an extension, the bar is said to be in tension, the stress is called tensile stress, and the corresponding strain a tensile strain.

In elastic material the ratio of stress to strain is a constant, a relation known as Hooke's Law, after its discoverer. This ratio is called the modulus of elasticity. Hence,

$$\frac{\text{stress}}{\text{strain}} = \frac{f}{S} = f.\frac{l}{\delta l} = \text{constant} = E \quad .... \quad (3)$$

where E is the tensile modulus of elasticity, often called Young's modulus.

It follows, therefore, that

$$\frac{f}{E} = \frac{F}{Ea} = \frac{\delta l}{l} \; ; \text{ or, } \quad \delta l = \frac{Fl}{Ea} \quad \ldots\ldots \qquad (4)$$

The magnitudes of f and E must be expressed in the same units, i.e. pounds per square inch. The value of the modulus of elasticity is different for different materials.

The above equations are strictly true if the stress over the cross section be uniform. If, as is often the case, the stress is not uniformly distributed, eq. (2) expressing the intensity of stress at any point must be written $f = \frac{\delta F}{\delta a}$, where δF is the amount of the molecular force on an indefinitely small area δa. Alternatively, in such a case as Figure (2), f in eq. (2) may be regarded as the average stress over the cross section.

Young's Modulus or the modulus of elasticity is a measure of stiffness or rigidity, the higher its value, the greater the stress needed to produce a given deformation and the stiffer the material.

2.1.3. COMPRESSIVE STRESS AND STRAIN. If the direction of application of the forces F F be reversed, the bar will be in compression instead of tension (iii, Figure 2). The alteration of length will be a contraction instead of an extension, and the stress and strain produced will be a compressive stress and compressive strain respectively. The ratio of compressive stress to compressive strain will be the compressive modulus of elasticity, which may be taken as equal to E, the tensile modulus. The same relation and equations will hold for compressive stress and strain as for tensile - in fact one may be regarded as a negative form of the other.

Pure tensile and compressive stresses and strains are sometimes called simple stresses and strains, for any state of stresses and strain can be reduced to combination of such simple stress and strains.

2.1.4. SHEAR STRESS AND STRAIN. Suppose A B C D to be a projecting length l of a body rigidly held at A D and acted on by force F at B, as shown in Figure (3). It will be assumed that the length l is so short that the bending set up is negligible. Under the action of the force F the body will deform the rectangle A B C D becoming the parallelogram A B'C'D'. This kind of deformation is called shearing, and the angle B A B' $= \delta\phi$, which is a measure of the deformation, is called the shear strain. The angle $\delta\phi$ is expressed in radians, and, since it will be very small, $\delta\phi = \frac{B\,B'}{A\,B}$. If a be the cross - section of the body, the average intensity of the shear stress is $fs = \frac{F}{a}$; and, as in the case of tensile and compressive stress and strain, it is found that, in elastic material, the ratio of shear stress to shear strain is constant. Hence,

$$\frac{\text{Shear stress}}{\text{Shear strain}} = \frac{fs}{\delta\phi} = \text{constant} = G \quad \dots\dots\dots\dots \quad (5)$$

or, $\delta\phi = \frac{fs}{G}$, where G is the modulus of elasticity in shear, often called the modulus of rigidity, a quantity corresponding to the tensile modulus E, but not equal to it.

Eq. (5) may be written

$$\frac{fs}{G} = \frac{F}{Ga} = \delta\phi = \frac{\delta y}{l} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (6)$$

where B B' is denoted by δ y.

2.1.5. THE STRESS - STRAIN RELATIONSHIP. The stress - strain relationship is described in many textbooks on engineering, materials and structures, physics and dental materials. Earnshaw [22] gives as a convenient example of stress - strain relationship, a wire in tension Figure (4). Assuming the wire is made of some non-ferrous metal. If it is loaded gradually in small increments, and if measurements are made of the extension produced by each increment, then a series of readings can be obtained, of load against extension, right up to the breaking load.

Knowing the original cross sectional area of the wire, loads can be converted to stresses and similarly, from the original length extensions can be converted to strains. The results obtained from loading the wire enable us to plot stress against strain for each load increment, and so draw a stress - strain curve for that material. A typical stress - strain curve for the material specified is shown in Figure (5). From a stress - strain curve like this we can define many properties which are important in consideration of metals and alloys under load.

The first part of the stress - strain curve, O A in Figure (5) is substantially a straight line. The material is obeying

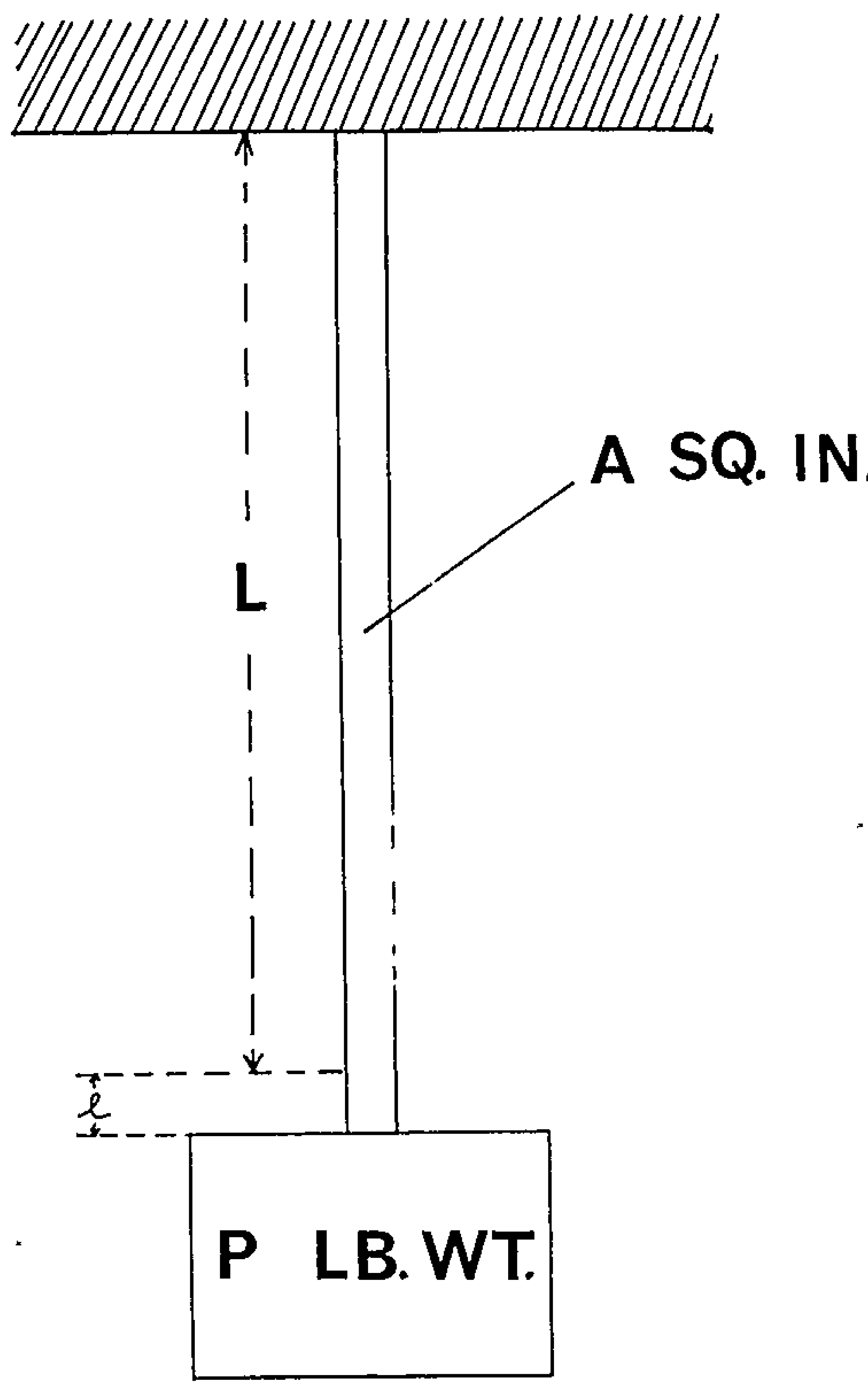


Figure 4. Wire in Tension.

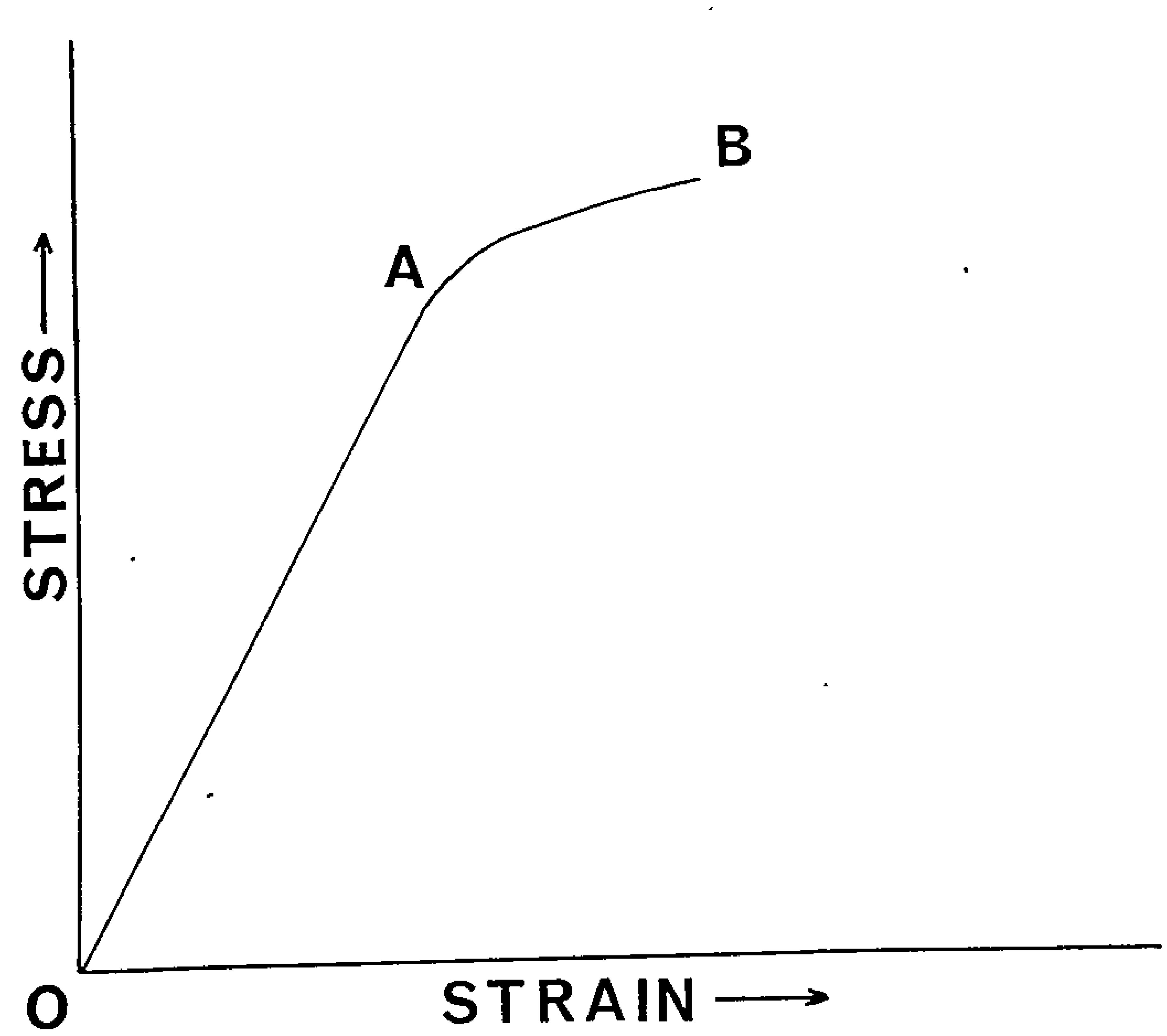


Figure 5. Typical Stress-Strain Curve.

Hooke's Law, and its behaviour is elastic. We call O A the elastic range; stresses in this range are elastic stresses; and we can say that only elastic deformation has taken place. If the load is removed at any time in the range O A, to all intent and purpose the strain returns to zero. If loads are re-applied, the new stress - strain curve follows the original one (i.e. the material is elastic).

Beyond the point A, the relationship between stress and strain is no longer linear, Hooke's Law no longer applies, and the behaviour of the material is no longer elastic.

The point A is called the proportional limit or the elastic limit.

Proportional limit can be defined as the maximum stress at which stress is directly proportional to strain.

Plastic deformation is occurring in the range A - B, but elastic strain is still present. If the load is removed at some stage in the plastic range, elastic recovery or "spring back" occurs, e.g. in Figure (6), if the load is removed at C the material recovers along the line C - D, parallel to the original elastic section O - A. Thus, after the load is removed there is still some strain present, measured by O - D; this represents the plastic deformation performed in the section A - C of the stress strain curve and is called permanent set, and is defined as the plastic deformation that remains upon releasing the stress that produces the deformation.

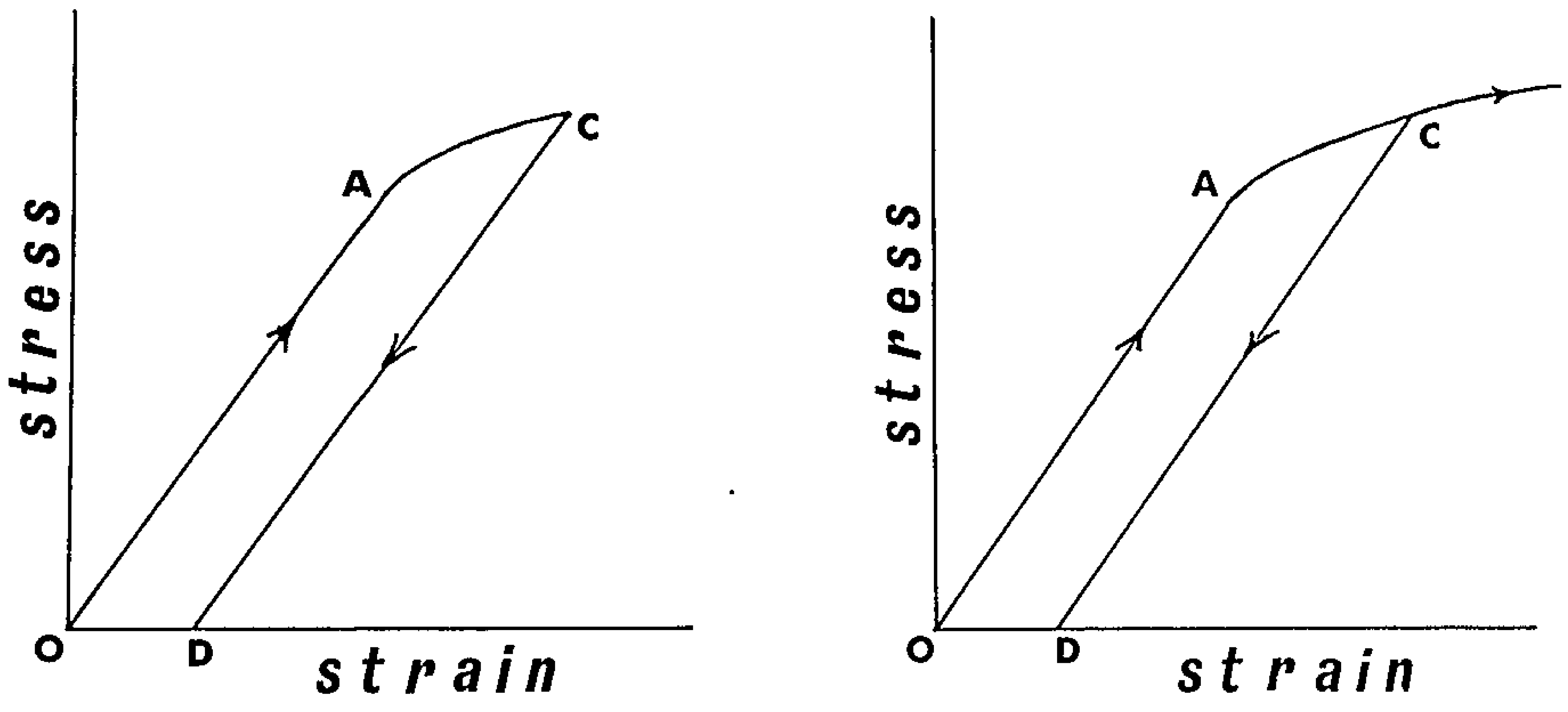


Figure 6. Stress-Strain Curve, Plastic Deformation.

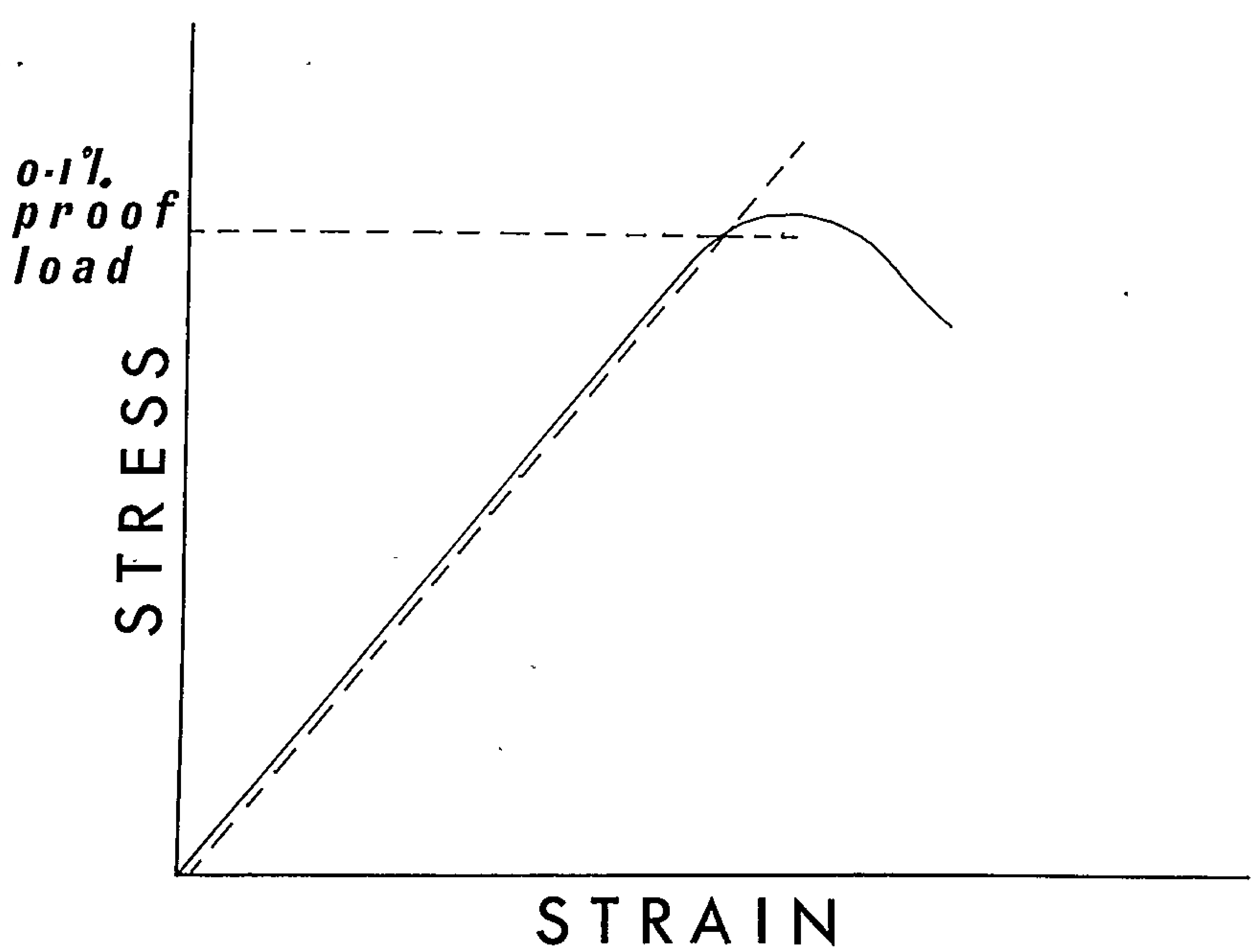


Figure 7. Stress-Strain Curve, Proof Stress.

If the material is then reloaded; the unloading curve is retraced from D to C. After the point C is reached the stress strain curve continues along C - B, just as if the original loading had not been interrupted.

2.1.6. ELASTIC LIMIT. The elastic limit is the maximum stress to which a material may be subjected without any permanent strain remaining upon complete release of stress. Salmon[46] states that the term "elastic limit" has been very loosely employed. It is sometimes used to denote -

(i) the limit within which the deformation entirely disappears when the load is removed;

(ii) the limit below which the elongation is proportional to the load;

(iii) the yield point, or as it is often called, the "commercial elastic limit".

In recent years (iii) is usually called the proportional limit. In mild steel is differs very little from (i). Very refined measurement, however, has shown that materials are only perfectly elastic under very low loads, for most materials very early develop minute permanent sets. Some experiments have given very low values for the elastic limit; but the term "proportional limit" is usually used to denote the point at which marked divergence from proportionality first appears. To avoid confusion it is better to speak of the "proportional limit" and "yield point", and not to use the terms "elastic limit" and "commercial elastic limit".

2.1.7. YIELD POINT. The yield point is the first stress in a material, usually less than the maximum attainable stress at which an increase in strain occurs without any increase in stress. Only certain metals exhibit a yield point. If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points.

2.1.8. YIELD STRESS. (Earnshaw)[22]. In order to get reproducible results, the stress is determined which produces a small, definite plastic strain. This will be a definite fixed point on the stress - strain curve, irrespective of how sensitive the measurements are. In effect, we select a very small but easily measurable plastic strain and say that any plastic deformation less than this is not serious. There are two common methods of assessing yield stress.

(a) The load is added in equal increments, and the stress noted at which increment first causes a strain twenty five per cent greater than the strain caused by that increment at the beginning of the test.

(b) The stress - strain curve is plotted as usual, and then a point is found on it corresponding to a definite plastic strain or permanent set of 0.001, i.e. of 0.1%. The stress necessary to produce this permanent set of 0.1% is called the 0.1% proof stress. It is easily found by drawing what is called an offset line on the stress - strain curve. (Figure 7).

In this case the offset line starts from a strain of 0.001 and is drawn parallel to the straight line part of the stress - strain curve. The point where it intersects the stress - strain curve corresponds to a permanent set of 0.001 (or 0.1%), and the stress at that point is the 0.1% proof stress. Sometimes a 0.2% proof stress is determined instead of 0.1%, or sometimes a smaller permanent set is defined, e.g. 0.02% or even 0.01%. Thus, there are two ways in which the yield stress can be measured. Both methods give similar results, since both are based on finding the stress which causes a small but easily measured plastic strain.

YIELD STRENGTH or YIELD STRESS. Can be defined as the stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2% is used for many metals.

2.1.9. PROOF STRESS. Can be defined as:-

(1) The stress that will cause a specified small permanent set in a material.

(2) A specified stress to be applied to a member or structure to indicate its ability to withstand service loads.

2.1.10. ULTIMATE TENSILE STRENGTH. Is the maximum conventional tensile stress that a material can withstand. Billberg[6] suggested that hard drawn stainless steel wires should have a proportional limit of eighty five per cent of their tensile strength. For springhard (high) tensile wires, ninety per cent is suggested.

Delgardo and Anderson[19] in tests on 18 - 8 stainless steel wires found that reverse bend tests gave some correlation to the ratio of proportional limit and ultimate tensile strength.

Wilkinson[68] in his work with stainless steel wires of different diameters, and from different manufacturers found that two important points emerged from the consideration of proportional limit and tensile strength. These were:-

(1) Tensile strength increases as the diameter of the wire is reduced, drawing conditions being equal. (This phenomenon is probably due to the relative depth of the plastic deformation, as the process of drawing causes pressures to be applied to the surface of the wire, its central core being the area least affected).

(2) .Tensile strength cannot be used as a reliable measure for proportional limit.

Manufacturers tend to supply strength data only, since it is much easier to determine tensile strength than proportional limit for wires.

2.1.11. DUCTILITY. Ductility is the ability of a material to deform plastically without fracturing, being measured by elongation or reduction of area in a tensile test or by other means.

Salmon[47] stated that one way of assessing ductility is to measure the total strain at fracture as a percentage and this gives the percentage elongation and gives an idea of the relative ductilities of different materials.

2.1.12. TOUGHNESS. Toughness is the ability of a metal to absorb energy and deform plastically before fracturing. It is usually measured by the energy absorbed in a notch impact test (Salmon)[48], but the energy under the stress - strain curve in tensile testing is also a measure of toughness. (Metals Handbook)[34]

If the amount of energy involved is large the material is tough. If the energy is small the material is brittle (Earnshaw).[22]

2.1.13. BRITTLENESS. Brittleness is the property of a material that permits crack-propogation without appreciable plastic deformation.

2.1.14. HARDNESS. Hardness is the resistance of metal to plastic deformation usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching,abrasion or cutting. Indentation hardness may be measured by various hardness tests, such as Brinell, Rockwell and Vickers, (Skinner, Salmon).[52], [48]

There appears to be a direct relationship between the ultimate tensile strength and the Brinell hardness number, such that the ratio of these quantities is approximately constant. (Salmon)[48]

Wilkinson[67] tested a specific 18 - 9 austenitic stainless steel orthodontic wire and found that for the range of temperatures and times selected the hardness of the wire was directly proportional to the tensile strength. For gold alloys it has been found that the Brinell Hardness number is directly proportional to the proportional limit and to the ultimate tensile strength (Bush, Taylor and Peyton).[15]

2.1.15. BEAMS. (Earnshaw)[22] A simple beam is one supported at each end, and loaded in the centre. (Figure (i) 8)

When a simple beam bends, there will be a neutral layer where the stress is zero. This can be imagined as an infinitely thin, horizontal layer through the centre of the beam. All parts of the the beam below the neutral layer will be in tension, and all parts above the neutral layer will be in compression.

In both cases, the stress increases with the distance from the neutral layer, and is at a maximum on the surface. In addition to those longitudinal stresses, shear stresses are set up as well, as a result of shear forces between the load and the supports.

A cantilever beam is one which is clamped at one end, and loaded at the other. (Figure (ii) 8). There is a neutral layer as before, and again the beam is in tension on one side of the neutral layer, and in compression on the other, and obviously shear stresses will be set up as well.

A clamped or encastre beam is one which is clamped, rather than just supported at each end. (Figure (iii) 8). Here the bending is more complex. There is still a neutral layer,

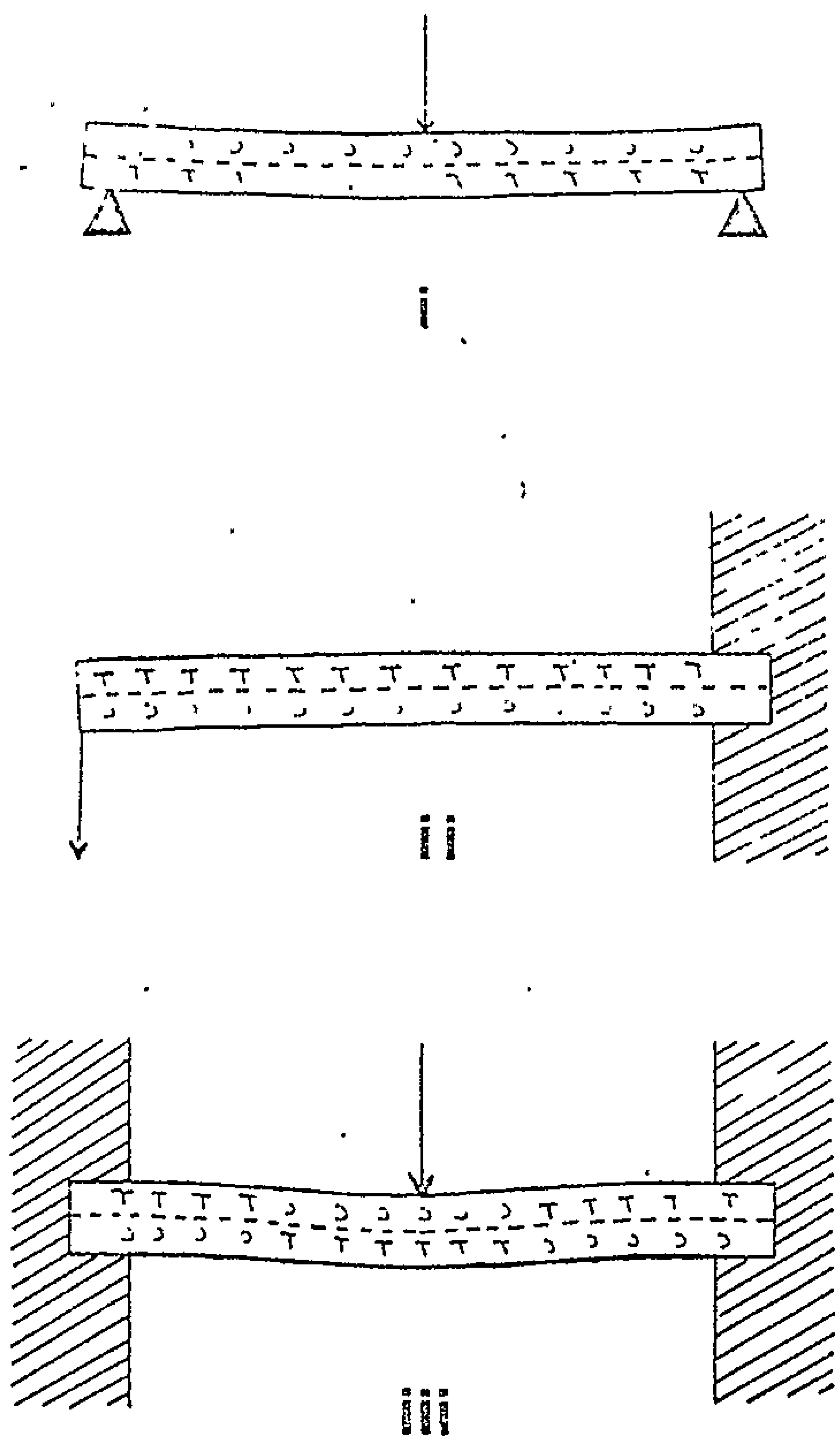


Figure 8. Beams-Bending.

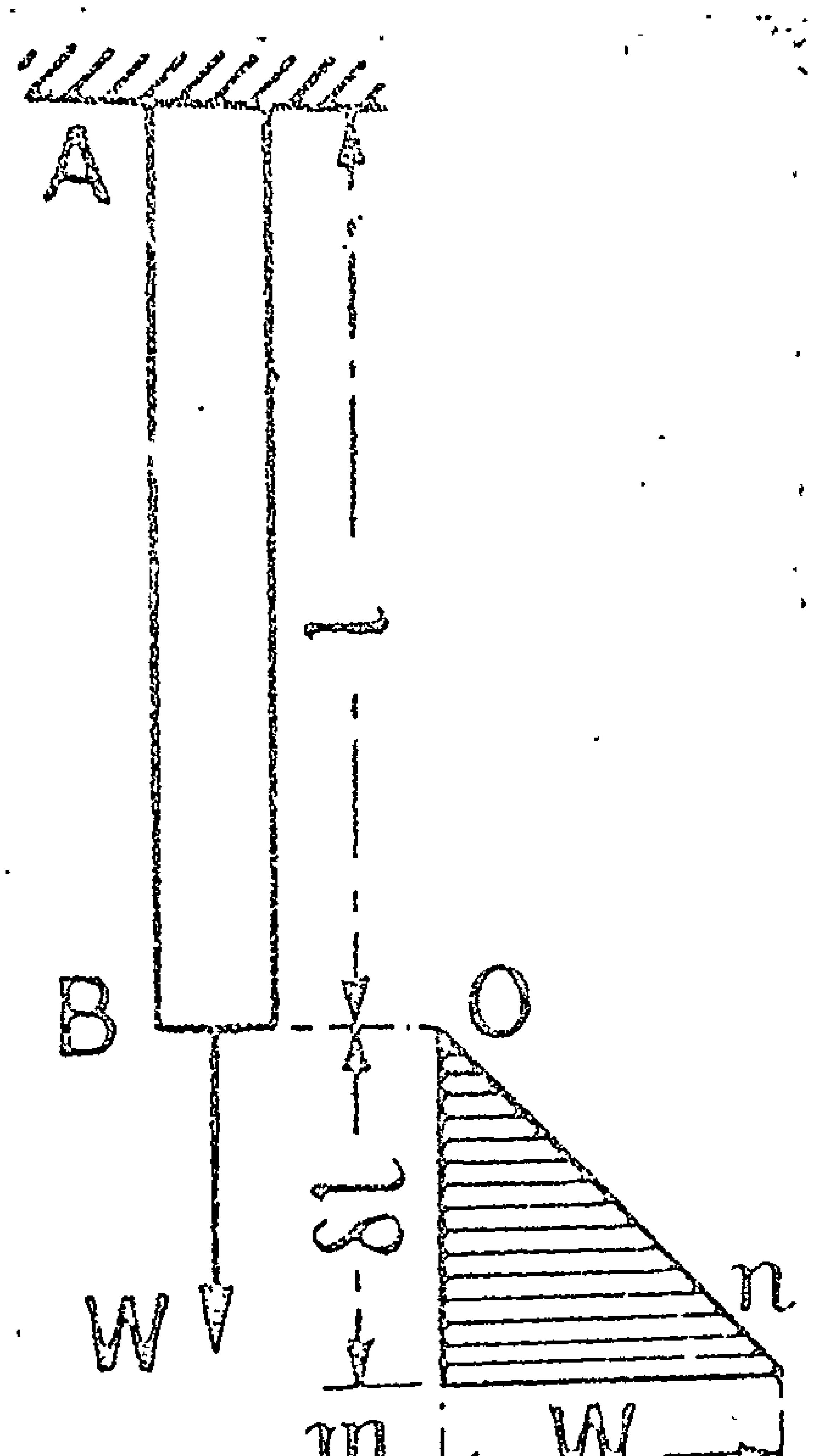


Figure 9. Work done in Stretching a Bar.

but the stresses on each side of it change in sign from section to section of the beam. Again, shear stresses are set up as well.

2.1.16. STRAIN ENERGY : RESILIENCE. Resilience can be defined as:-

(1) The amount of energy per unit volume released upon unloading.

(2) The capacity of a metal, by virtue of high yield strength and low elastic - modulus, to exhibit considerable elastic recovery upon release of load.

WORK DONE IN STRETCHING A BAR. (Salmon)[49] Let A B (Figure 9) be a bar of length l, attached at its upper end A, and loaded at its lower end B, with a tensile force which gradually increases from zero to some value W. As the load increases the bar will lengthen; and, while the material remains elastic, the stress will be proportional to the strain, therefore the increase in length δl will be proportional to the load W. The triangle o m n will represent the relation between δl and W, that is to say, the increase in l for increasing the values of W. Now the work done on the load in stretching the bar is equal to the average force W/2, multiplied by δl the distance moved. Hence the work done is $\frac{1}{2}\,W.\delta l$ which is equal to the area of the triangle o m n. This energy is stored up in the bar and is called the strain energy. If the area of the bar be a, and the stress due to the load W be f, then W = fa. Further the stress is equal to E times strain, and the strain is $\frac{\delta l}{l}$. Therefore,

$f = E\frac{\delta l}{l}$, and $\delta l = \frac{fl}{E}$. If U be the strain energy,

$U = \frac{1}{2} W.\delta l = \frac{1}{2} fa \frac{fl}{E} = \frac{f^2}{2E}$. $al = \frac{f^2}{2E}$ X (volume of the bar)

for a.l is the volume of the bar, or as it is sometimes called the internal work. If the load W. be increased until the stress f reaches the upper limit of elasticity of the material, the strain energy then stored up in bar will be the minimum amount of work which can be done on the bar without permanently deforming it. This amount of work is called the resilience of the bar. The load producing this stress is the proof load W_p, and the stress is called the proof stress f_p. If U_p be the resilience

$$U_p = \frac{f_p^{\,2}}{2E} \;.\; \text{(Volume of the Bar)}$$

The resilience is a measure of the capacity of the member to store up work, and therefore of its capability to resist shock, without plastic deformation, for should the bar sustain a blow, the energy imparted to it by the shock must not exceed the resilience, or the bar will be permanently deformed.

Wahl[63] considers the above case to be an ideal spring, since the bar is loaded axially, the stress distribution across the section is uniform and for this reason this case represents the optimum condition from the viewpoint of maximum storage per unit volume of material. He compares the energy storage capacity of various types of springs, and states that if comparison is made on the basis of energy stored at first yielding (the extreme fibre is stressed to the yield point) it appears that the simple tension bar spring (Figure 9) is far more efficient than other types. On the other hand, if comparison is made on the more logical basis of energy storage for complete yielding over the section, it appears that the ideal spring is not a great deal more efficient than other types. He emphasises the fact that in the choice of spring type by the designer that a great many factors are involved besides energy storage per unit volume.

2.2. BENDING MOMENTS AND SHEARING FORCES. (Salmon)[50]

Let AB (Figure 10) be a cantilever projecting from a wall, and suppose that a couple M be applied at A. The effect of this moment will be to bend the beam as shown in that figure. Such a moment is called a bending moment. It is evident that a similar effect will be produced if, instead of the couple, a vertical load W be applied at A (Figure 11). Consider any section K at a distance x from W. The equilibrium of the portion A K of the beam (ii, Figure 11) will not be affected if two equal and opposite forces, of the same magnitude as W be applied to the beam at K. If the upward force W at K be considered in conjunction with the downward force W at A, the two forces evidently form a couple of magnitude Wx, and this couple will cause the beam to bend, just as did the couple M in Figure 10. The moment Wx of the couple is evidently the bending moment on

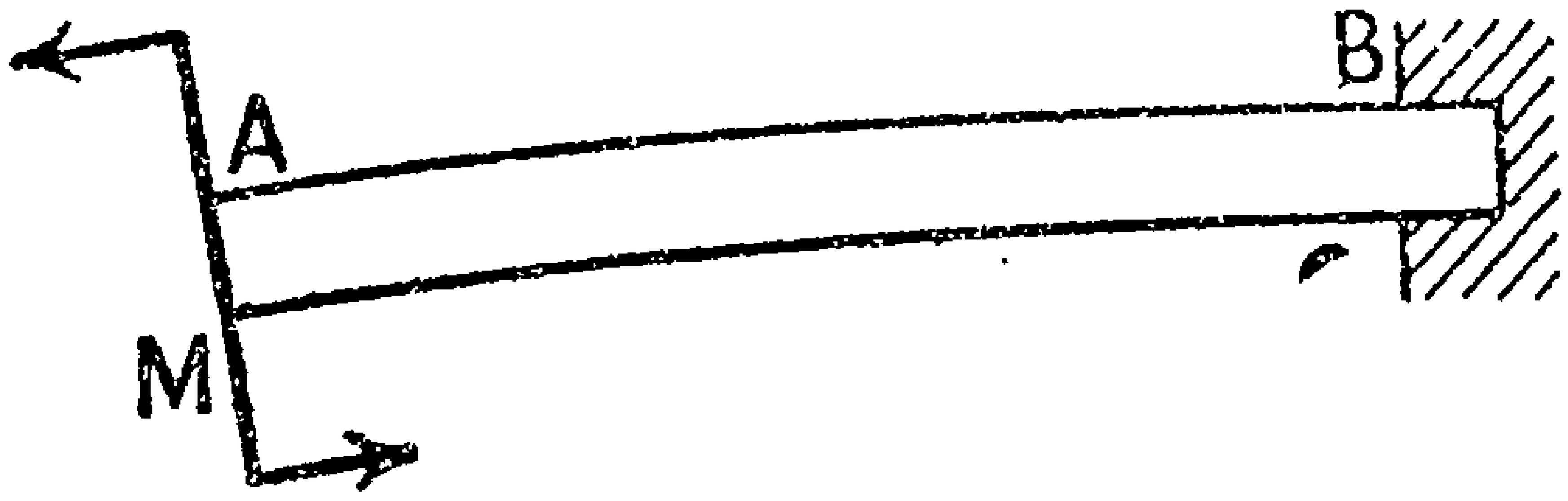


Figure 10. Bending Moment of a Cantilever Beam.

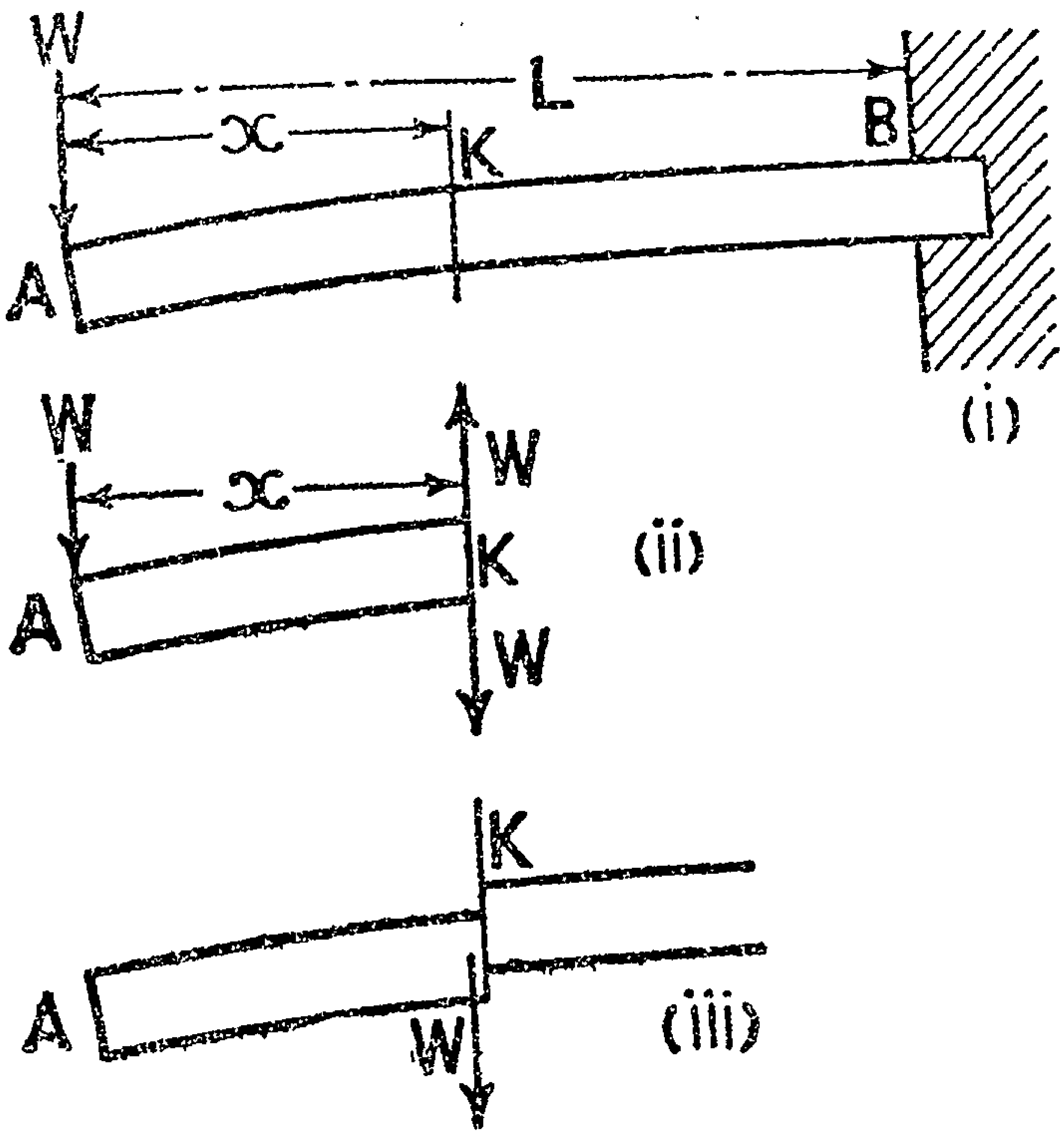


Figure 11. Effect of a Load on a Cantilever Beam.

the beam at the section K.

There still remains the third force W, at K, to be taken into account. This will tend to slide the portion A K of the beam downwards, relatively to the remainder, as shown at (iii), Figure 11. It tends in fact to shear the beam at K, and is the shearing force at that section.

The load W at A, therefore, has two effects on the beam at a section such as K. It produces a bending moment which curves the beam, and shearing force which tends to shear the beam.

Next, suppose that there be more than one load on the cantilever (Figure 12), say W_1 at distance x_1, from K and W_2 at a distance x_2 from K. As before, consider the equilibrium of the portion A K (ii, Figure 12), and suppose that two equal and opposite forces of magnitude $(W_1 + W_2)$ act at K. There are, then, two couples acting on the portion A K, of which the moments are $W_1\ x_1$ and $W_2.x_2$, and the total bending moment at K is $(W_1\ x_1 + W_2\ x_2)$, or the sum of the moments due to W_1 and W_2 considered separately. Further, the shearing force at K is evidently $(W_1 + W_2)$ or the sum of the loads W_1 and W_2.

If W_2 act in the reverse direction to W_1 (iii, Figure 12), it is evident that it would produce a moment and a shearing force of the opposite kind to that produced by W_1. If the kind of bending and shearing produced by W_1 be considered positive, that produced by W_2

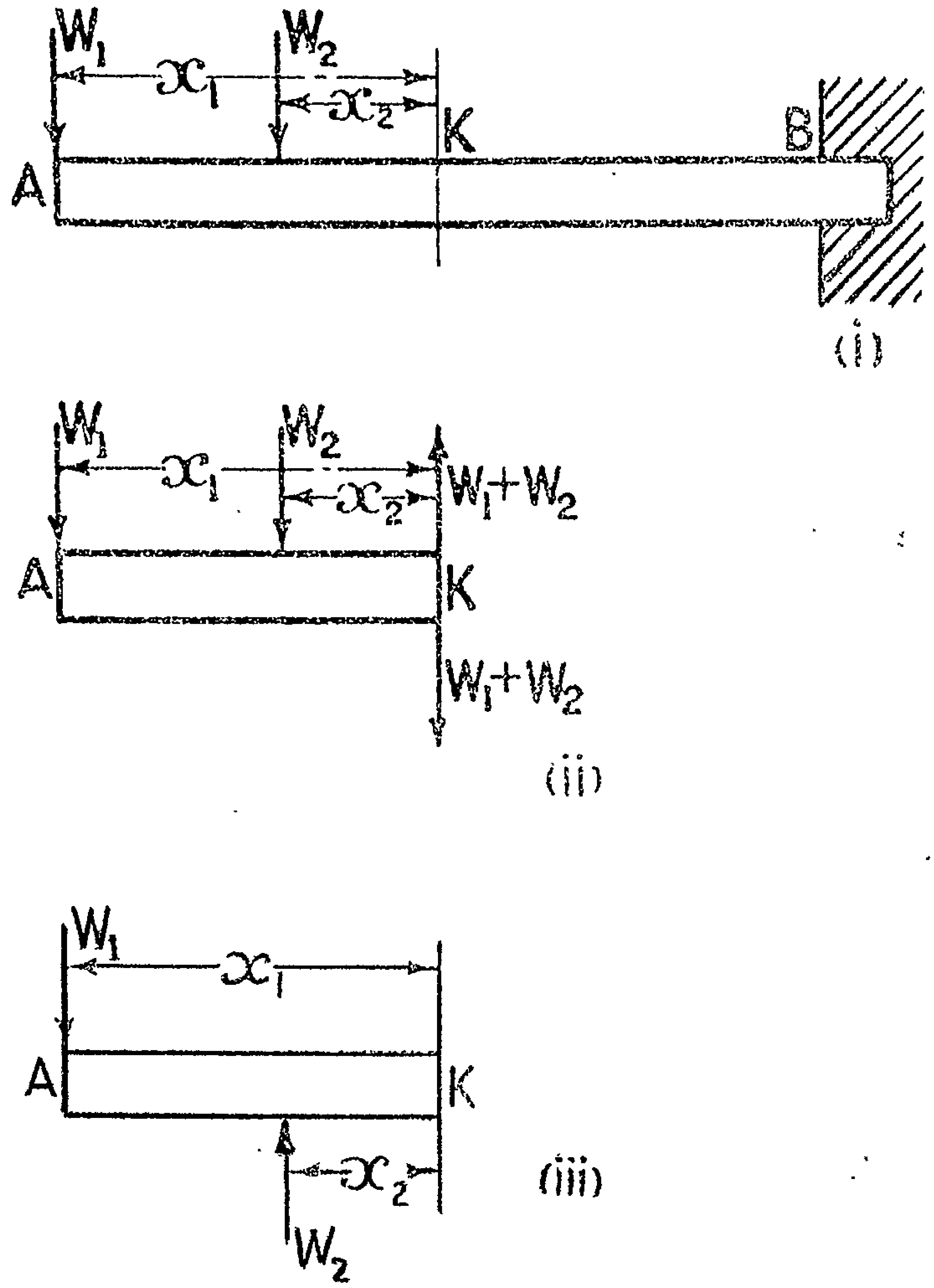


Figure 12.

Effect of more than one Load on a Cantilever Beam.

Figure 13.

Positive and Negative Bending and Shearing.

must be considered as negative, Figure 13 represents positive and negative bending and shearing. These signs are, of course, merely conventions.

By extension from the above reasoning, when all the forces are perpendicular to the beam, the bending moment at any section of the beam may be defined as the algebraical sum of the moments about that section of all forces acting on the beam to the right (or, alternatively to the left) of the section; and the shearing force at any section of a beam may be defined as the algebraic sum of all the forces acting on the beam to the right (or, alternatively to the left) of the section.

2.3. STRESSES DUE TO BENDING. (Salmon)[50]

2.3.1. THE STRESSES ON A CROSS SECTION, UNIPLANAR BENDING.

Suppose K_oJ_o (Figure 14) to be small element of length in a beam originally straight. A bending moment M acts on the element, distorting it in shape to $K_1J_1J_2K_2$. It will be assumed that plane sections of the beam remain plane after bending. That is to say, the plane sections $K_1\ K_o\ K_2$, $J_1\ J_o\ J_2$, which are perpendicular to the curved axis of the beam, were plane sections of the beam before distortion, and were perpendicular to the axis, which was then straight.

The outer layer of fibres K_1J_1 will be extended by the bending moment, whilst the inner layer of fibres $K_2\ J_2$ will be compressed. One layer of fibres between these two extremes will be neither

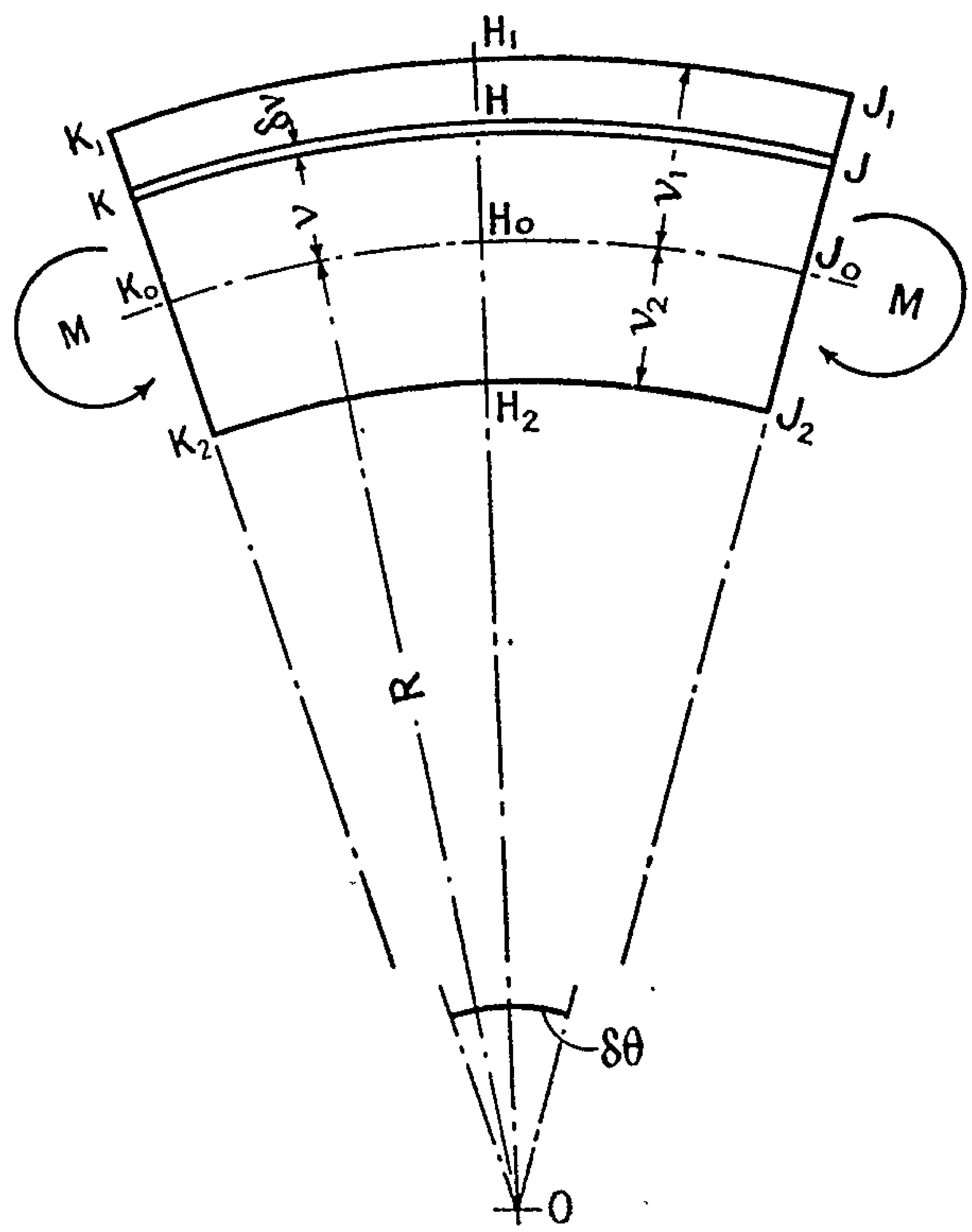


Figure 14.
Stress on a Cross-section; Uniplanar Bending.

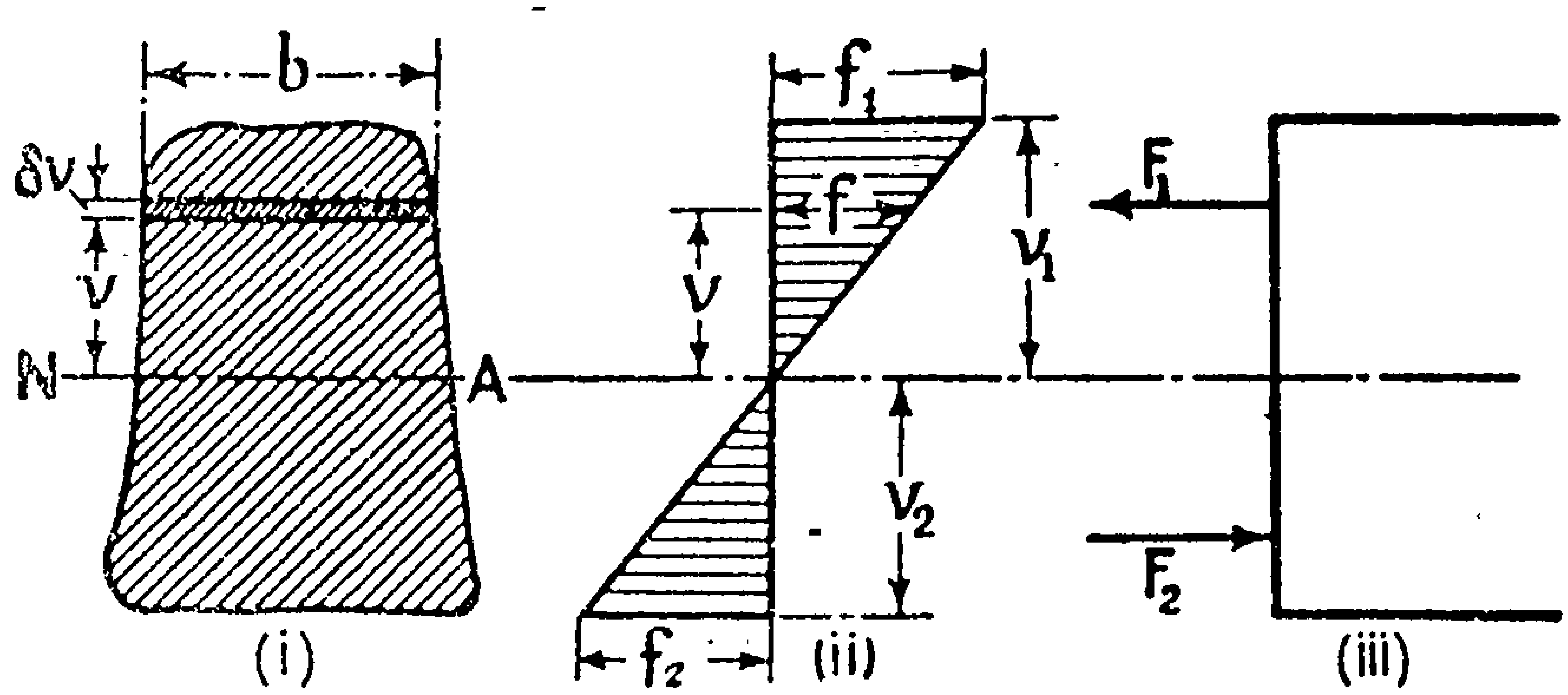


Figure 15.
Variation in Stress due to Bending.

extended nor compressed, it will be unaltered in length. Let $K_o\ H_o\ J_o$ be this layer. O, the centre of curvature of the element, will lie on the intersection of the two planes $K_1\ K_o\ K_2$ and $J_1\ J_o\ J_2$. $O\ H_o = R$ will be the radius of curvature of the layer $K_o\ H_o\ J_o$. Let the angle $K_o\ O\ J_o$ be $\delta\theta$.

Consider a layer of fibres K H J distant v from the layer $K_o\ H_o\ J_o$. The original length of this layer was the same as that of the layer $K_o\ H_o\ J_o$, and the latter is unaltered in length by the bending moment. Therefore, the original length of both layers $K_o\ H_o\ J_o$ and K H J was $R.\delta\theta$. The strained length of the layer K H J is $(R + v)\delta\theta$. Hence, the alteration in length of this layer is $(R + v)\delta\theta - R.\delta\theta = v.\delta\theta$, and the strain in it is

$$\frac{\text{alteration in length}}{\text{original length}} = \frac{v.\delta\theta}{R.\delta\theta} = \frac{v}{R}$$

If E, the modulus of elasticity of the material, be assumed constant, and f be the stress in the layer, then

$$f = E \times \text{strain} = E.\frac{v}{R}; \quad \text{or} \quad \frac{f}{v} = \frac{E}{R} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

Since $\frac{E}{R}$ is constant for the element under consideration, f varies as v; that is to say, the stress in any layer of fibres varies directly as the distance of that layer from the layer unaltered in length by the bending moment. The diagram (ii, Figure 15) representing the variation in stress, is a straight line. At the layer $J_o\ H_o\ K_o$ (Figure 14), $v = o$, and the stress is zero. This layer of fibres is called the neutral surface, and its intersection with the plane of bending is called the neutral line. The line N.A (i, Figure 15), which represents the section of the neutral surface by any right transverse cross - section, is called the neutral axis. For layers of fibres above the neutral surface, v is positive; and if, as in Figure 14, the bending moment is positive, the stress is tensile (positive). For layers of fibres below the neutral surface, v is negative; and the stress is compressive (negative). This is clearly shown by the double triangle of (ii) Figure 15), which represents the variation of stress over the cross-section. The maximum tensile stress f_1 will occur in the extreme layer of fibres, $v = v_1$, on the extended side of the beam.

From equation (7)

$$f_1 = \frac{E\,v_1}{R} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (8)$$

Similarly, the maximum compressive stress f_2 will occur in the extreme layer of fibres in compression $v = -v_2$, its magnitude is

$$f_2 = \frac{-\,E\,v_2}{R} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (9)$$

the negative sign denoting compression.

2.3.2. POSITION OF NEUTRAL AXIS. Let b (i, Figure 15) be the breadth of the layer of fibres distant v from the neutral axis. If δv be the thickness of the layer, its area is $b.\,\delta v$. The force on this layer is $fb.\,\delta v$, where f is the stress therein.

Hence the total force F_1 (iii, Figure 15) on that part of the cross - section above the neutral axis is

$$F_1 = \int_{o}^{v_1} fb.\ dv. = \frac{E}{R} \int_{o}^{v_1} bv.\ dv. \quad \ldots\ldots \quad (10)$$

similarly, the total force on that part of the cross - section which is below the neutral axis is

$$F_2 = \int_{o}^{-v_2} fb.\ dv. = \frac{E}{R} \int_{o}^{-v_2} bv.\ dv. \quad \ldots\ldots \quad (11)$$

The total longitudinal force on the cross - section of the beam will be $F_1 + F_2$, but since these forces are produced by a bending moment only, and no longitudinal force exists, it follows that

$$F_1 + F_2 = 0 \ ; \quad \text{or} \quad F_1 = - F_2 \quad \ldots\ldots\ldots\ldots\ldots \quad (12)$$

and that,

$$F_1 + F_2 = \frac{E}{R} \int_{o}^{v_1} bv.\ dv. + \frac{E}{R} \int_{o}^{-v_2} bv.\ dv.$$

$$= \frac{E}{R} \int_{-v_2}^{v_1} bv.\ dv. = 0$$

from which

$$\int_{-v_2}^{v_1} bv.\ dv. = o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

but $\int_{-v_2}^{v_1} bv.\ dv. = a\bar{v}$, where a is the area of the cross - section, and $\bar{v}$ is the distance of its centre of area from the neutral axis. Hence, from equation (13) $a\bar{v} = 0$, $\bar{v} = 0$. That is to say, the neutral axis passes through the centre of area of the cross - section. Since the bending is uniplanar, the neutral axis will be perpendicular to the plane of bending.

2.3.3. THE MOMENT OF RESISTANCE. The bending moment upon the element will be resisted by an equal and opposite moment of the internal stresses set up in the beam. This moment of the internal stresses is called the moment of resistance. It is evidently the moment of the resultant tensile and compressive forces F_1 and F_2 (ii, Figure 15) which act on the cross - section. These have been shown to be equal (Equation 12). Therefore, they form a couple, and moments may be taken about any point. Take moments about the neutral axis. The force on a layer of fibres distant v from the neutral axis has been shown to be $fb. \delta v. = \frac{E}{R} bv. \delta v.$ The moment of this force about the neutral axis is $fbv. \delta v. = \frac{E}{R} bv^2. \delta v.$ Hence the total moment of all such forces on the cross - section, which is the moment of resistance, is

$$\frac{E}{R}\int_{-v_2}^{v_1} bv^2.\ dv. \quad \text{But} \int_{-v_2}^{v_1} bv^2.\ dv = I,$$

where I is the moment of inertia of the cross - section about an axis through its own centre of area perpendicular to the plane of bending, i.e. about the neutral axis. Hence the moment of resistance, which is equal to the bending moment M, is $\frac{EI}{R} = M$; and it follows from Equation (7) that

$$\frac{M}{I} = \frac{E}{R} = \frac{f}{v} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (14)$$

$$F = \frac{Mv}{I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (15)$$

At the extreme fibres in tension, $f = f_1$, and $v = v_1$.

Therefore,

$$f_1 = \frac{Mv_1}{I} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (16)$$

Similarly, at the extreme fibres in compression

$$f = f_2 \quad \text{and} \quad v = -v_2$$

Therefore, $$f_2 = -\frac{Mv_2}{I} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (17)$$

Now $\frac{I}{v_1}$ and $\frac{I}{v_2}$ are called the moduli of resistance or section moduli of the cross - section and are represented by the letter Z_1 and Z_2 respectively.

Hence, $$M = f_1 Z_1 = f_2 Z_2 \qquad \ldots\ldots\ldots\ldots\ldots \qquad (18)$$

From these equations the stresses in a beam due to bending can be determined.

The foregoing is usually referred to as the <u>Theory of Simple Bending</u>. A number of assumptions have been made or implied and the theory is only approximate. Nevertheless as proved by practice and experiment, it is sufficiently accurate for ordinary engineering problems and may with confidence be applied to them. A more exact theory, taking into account the shear stresses, has been given by Saint-Venant, and will be found in treatises on the Theory of Elasticity.[61]

2.3.4. THE MOMENT OF INERTIA. The moment of inertia of the cross - section about a principle axis through the centre of area is given by the integral, $I = \int_{-v_2}^{v_1} bv.^2 \; dv.$ (see 2.3.3.) For simple cross - sections this integral can be evaluated directly (Salmon).[50] In more complicated cases direct integration may not be convenient or even possible.

2.3.5. CALCULATION OF BENDING STRESSES IN A BEAM. Given a beam loaded in any specified manner, to find the maximum bending stresses on any cross - section. From the given load system, find M the bending moment at the cross section. Calculate the values of the section moduli Z_1 and Z_2 from the dimensions of the cross - section. Then from Equation 18, the stresses at the extreme fibres of the cross - section are $f_1 = \frac{M}{Z_1}$; $f_2 = \frac{M}{Z_2}$; or alternatively from Equations 16 and 17

$$f_1 = \frac{M\ v_1}{I} \qquad \text{and} \qquad F_2 = \frac{M\ v_2}{I}$$

One of these will be the maximum bending stress on the cross - section.

2.4. DEFLECTION OF BEAMS (Salmon)[50]

CURVATURE. Let J K H (Figure 16) be part of the deflection curve of a beam, and K and H any two neighbouring points on that curve. Let the co-ordinates of K be x and y, and those of H be $(x + \delta x)$, $(y + \delta y)$. The ordinate y is the deflection of the beam from the straight line Ox at a point distant x from the origin O. Draw K T_1 H T_2 tangents to the curve at K and H respectively, and produce

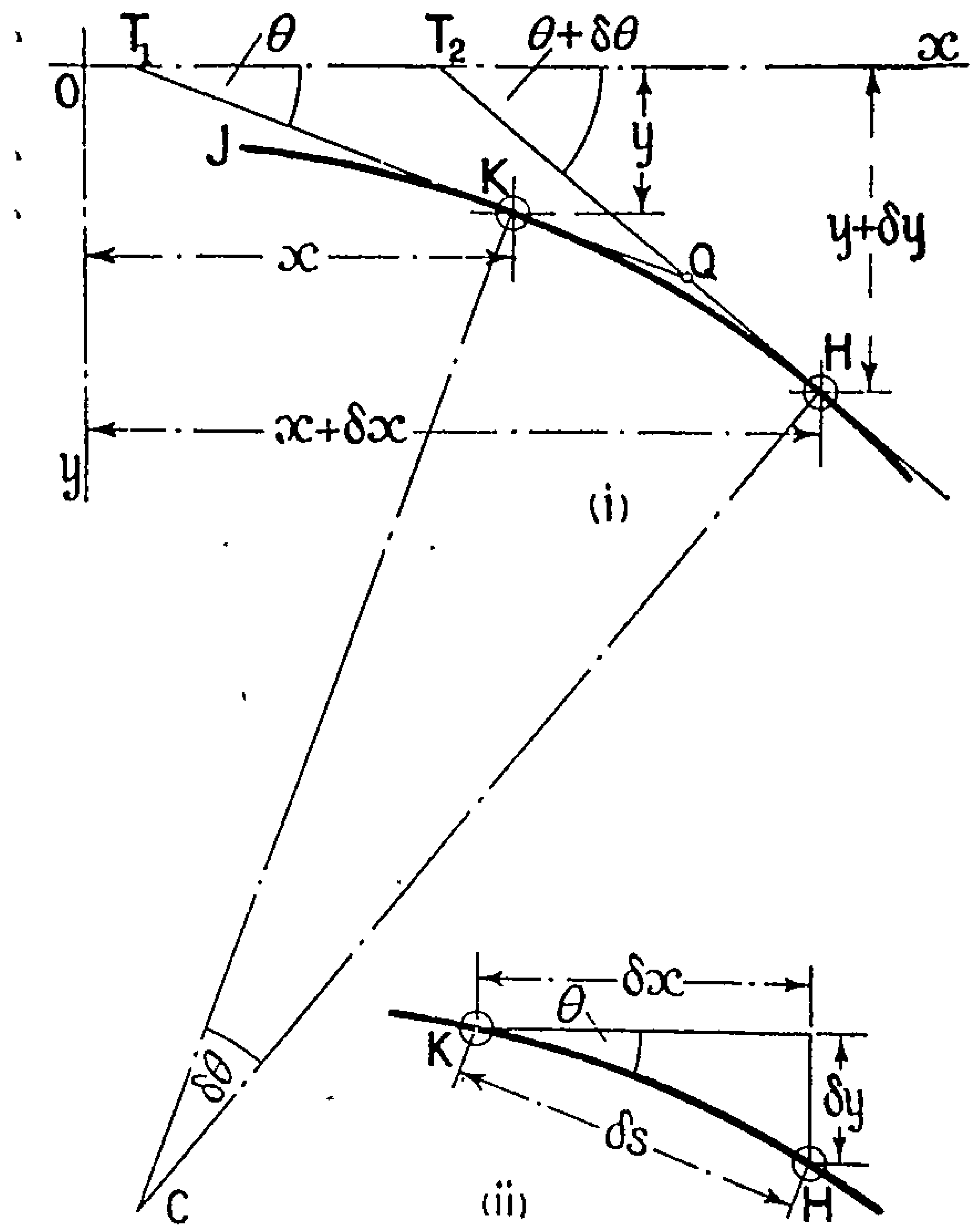


Figure 16. Deflection of Beams - Curvature.

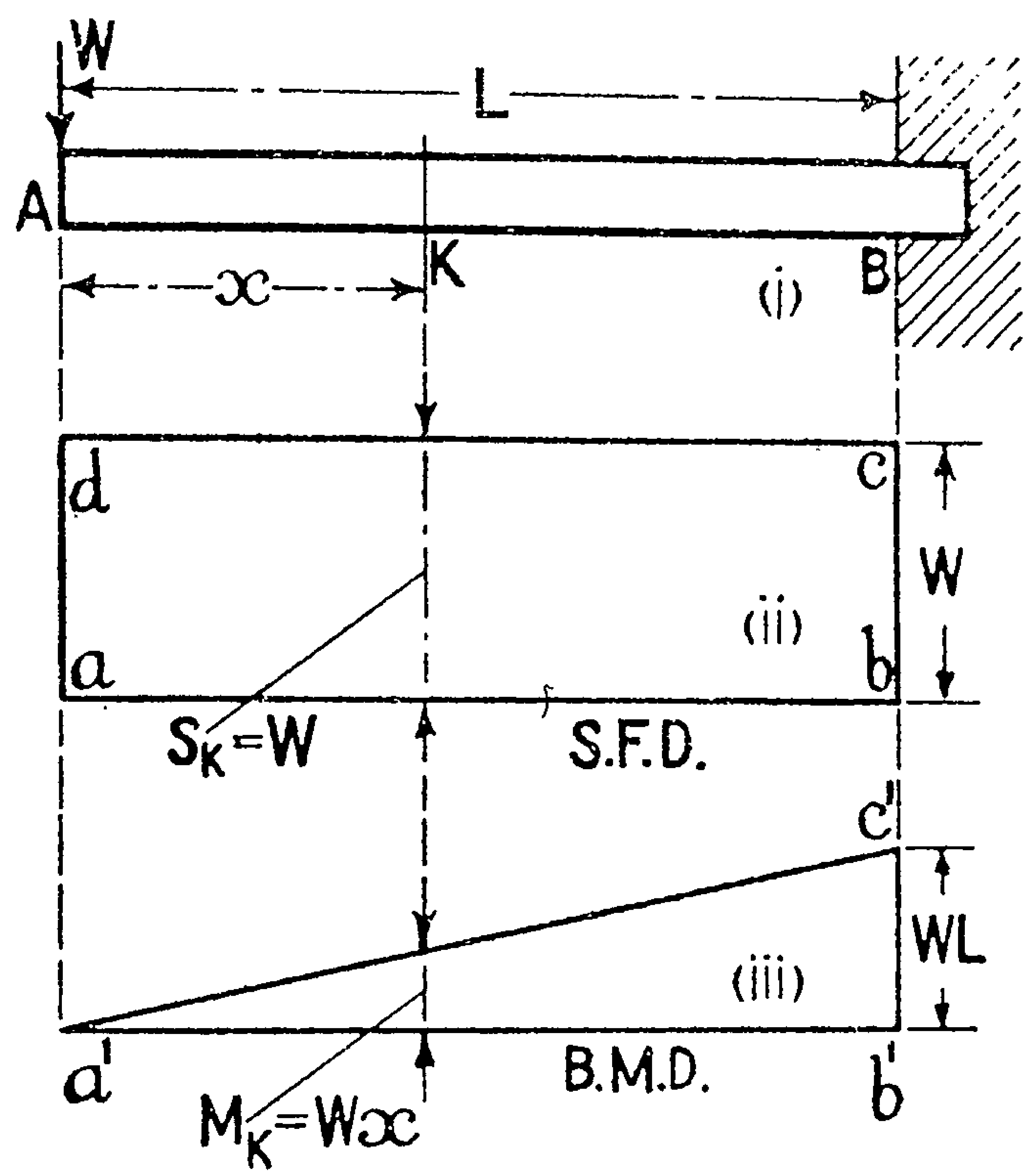


Figure 17. Bending Moment and Shearing Force Diagrams of a Cantilever Spring.

T_1 K to meet T_2 H in Q. Let the angle K T_1x be θ and H T_2x be $(\theta + \delta\theta)$. Then the angle H T_2x is equal to the angle K T_1x plus the angle T_1Q T_2. Hence the angle T_1Q T_2 $= \delta\theta$

Draw K C and H C perpendicular to K T_1 and H T_2 respectively; the angle K C H is equal to $\delta\theta$.

Let K H $= \delta$s. Then if C K = R., $\delta\theta = \frac{KH}{CK} = \frac{\delta s}{R}$ and $\frac{1}{R} = \frac{\delta\theta}{\delta s}$. In the limit when $\delta\theta$ is very small, K and H become consecutive points, R becomes the radius of curvature at K, and

$$\frac{1}{R} = \frac{d\theta}{ds} \qquad \text{.....................} \qquad (19)$$

Now $\tan\theta = \frac{dy}{dx}$, differentiate with respect to S,

$$\sec^2\theta . \frac{d\theta}{d\,s} = \frac{d^2y}{dx^2} \quad \frac{dx.}{d\,s}$$

In the limit, when δ x is very small, $\frac{\delta x}{\delta s}$ becomes

$$\frac{dx}{ds} = \cos\theta \qquad \text{(ii, Figure 16)}$$

Hence $\frac{d\theta}{ds} = \frac{d^2y}{dx^2} \quad \frac{1}{\sec^3\theta} = \frac{d^2y}{dx^2} \quad \frac{1}{(1 + \tan^2\theta)\ 3/2}$ or,

from Equation 19

$$\frac{d\theta}{ds} = \frac{1}{R} = \frac{\frac{d^2y}{dx^2}}{\left\{1 + (\frac{dy}{dx})^2\right\}\ 3/2} \qquad \text{........} \qquad (20)$$

1/R is usually called the curvature of the beam at the point K. Equation 20 is the ordinary expression for the curvature in terms of the co-ordinates of the curve. In a beam, the curvature is always very small, and θ is a very small angle. Therefore $\tan\theta$ $= \frac{dy}{dx}$ is very small, and $(\frac{dy}{dx})^2$ can be neglected in comparison with unity. Equation 20 then reduces to

$$\frac{1}{R} = \frac{d^2y}{dx^2} = \frac{M}{E\ I} = \frac{f}{Ev} \quad \ldots\ldots\ldots\ldots\ldots \quad (21)$$

since, from Equation 14, $\frac{M}{I} = \frac{E}{R} = \frac{f}{v}$

The deflection of the beam can be found by solving the differential equation (21).

CHAPTER 3

STRUCTURAL INTERPRETATION OF PHYSICAL PROPERTIES OF MATERIALS.

In general, a structure may be defined as the definite arrangement of material in a form adapted to the accomplishment of a purpose by the transmission or absorption of force (Brumfield)[8]. The form of the structure as well as its material is important in carrying out this purpose and both these factors must be considered in determining the ability of a structure to accomplish its purpose.

3.1. STRENGTH OF STRUCTURE - ELASTIC AND INELASTIC

Structural strength may be defined as the maximum load, of a given character, which the structure can carry (Brumfield)[8]. Since the structure may be required to carry more than one type of load, it is obvious that it may have more than one strength. It is usually true, however, that one of the types is a critical or controlling one, and strength will be interpreted in terms of this load type. There are two distinct types of strength under steady load. These are elastic strength and inelastic strength. The elastic strength of the structure would be the biggest load of controlling type which the structure can support without permanent distortion. The inelastic strength of the structure would be the load of critical type to rupture the structure. In bending which is the loading type ordinarily used in orthodontic structures, the strength would be limited to that load which would induce the proportional limit stress at any point within the structure. This strength depends on the material and on the form of the structure. However, in comparing two structures identical in form but of different materials, the influence of the form of the structure would cancel, for purposes of comparison, and the elastic strength would then vary directly as the proportional limits of the materials. In a similar manner, inelastic strengths on a comparative basis, for identical structures of different materials, vary directly as the ultimate strengths of the materials of which the two structures are made. Though structural form may have an influence on strength, the physical properties of the materials become useful from a comparative standpoint, when structural forms have considerable similarity.

While the proportional limit is a measure of the upper limit of elastic strength, Brumfield[8], and Smith and Storey[58], both caution against applying the full elastic load to any structure. This is particularly true of orthodontic structures because of uncertainties surrounding the structure in use in the mouth. If a load greater than the elastic strength of the structure is inadvertantly applied the structure would distort permanently and fail to carry out its intended function. It is a common practice that the working load of a spring be somewhat below the full elastic - strength (Wahl)[64].

3.2. FLEXIBILITY OF STRUCTURE

The flexibility of structure is the amount of distortion, of any given character, which the structure undergoes when a load within its elastic strength is applied to it (Brumfield)[8]. The term is usually reserved for distortion due to bending. Flexibility depends on the physical properties of the materials of which the structure is fashioned and on the general form and detailed dimensions. The two properties of materials which are pertinent to the flexibility of all structures are proportional limit and modulus of elasticity. The higher the proportional limit the greater the flexibility under given conditions. Inversely, the higher the modulus of elasticity the less the flexibility, other conditions being constant. The flexibilities of most orthodontic structures are in the main, required under conditions which bring bending forces to bear on the structural parts. The general law of flexibility in bending is

$$y = K \frac{f_p L^2}{Ev} \quad \ldots\ldots\ldots\ldots \quad (22)$$

where y is the flexibility of the structure

f_p is the proportional limit of the material

L the length of the structure under bending

v the depth of the structure (for symmetrical sections) in the plane in which bending occurs. The values of v may be constant or variable depending on conditions.

K is constant for any given structure. It reflects the type of loading and type and manner of supports at the ends of the beams. In the case of a cantilever beam, with a single concentrated load at the end K is 1/3. For more complicated structures, the value of K may be difficult to determine. Nevertheless, the equation is useful for comparative purposes. If it is desired to make a comparison of the possible flexibilities of two structures from different materials, but in identical structural forms, the value of K, whatever it may be, will cancel and the physical properties of the materials become the determining factors in making the comparisons. Such comparisons are of value for semi - design purposes. (Brumfield[9] gives tables enabling comparison of various types of materials suitable for a range of orthodontic springs.)

3.3. COMPARATIVE DESIGN OF STRUCTURES FROM WROUGHT WIRE.

Orthodontic structures are primarily subjected to bending loads and their detailed dimensions are determined by bending stresses. For structures loaded in bending the following general law applies (Brumfield)[10]

$$W = K f_p \frac{I}{V} \qquad \text{...........} \qquad (23)$$

or, for a circular section,

$$W = K_1 f_{p1} d^3 \qquad \text{...........} \qquad (24)$$

In the above equations 23 and 24, W represents the load of any given character which the structure may safely carry in bending and is therefore, its strength; f_p is the proportional limit of the material of which the structure is built; $\frac{I}{V}$ is the section modulus of the structure perpendicular to the plane in which maximum bending occurs; and K is a constant which depends on the kind of loading, the general character of the structure and the method of supporting it. In the second equation K is a similar constant but not the same one; d is the depth of the structure, (for a circular section $\frac{I}{V}$ is equal to $\frac{d^3}{32}$ for bending).

Both these equations may be used for comparing two structures whose forms are sufficiently alike that their K - values are the same. If it is assumed that a satisfactory orthodontic appliance has been worked out in terms of a given material, the necessary dimensions of a similar structure from a different material may be determined by comparison. Brumfield believes that flexibilities of structures may be compared quite successfully so long as their general form remains the same.

3.3.1. BENDING MOMENT OF A CANTILEVER SPRING. (Salmon)[50]

As an example consider a cantilever, length L, loaded with concentrated load W at its free end. The shearing force and bending moment diagrams for this case are given in (ii) and (iii) Figure 17. At any section K, distant x from A, the shearing force is equal to W, hence the shearing force diagram is a rectangle a b c d. The bending moment M_k, at K, is W X. Hence the bending - moment diagram is a triangle a'b'c', the ordinate at a', where x = o, is zero, and at b', where

$x = L$, is w.L. This is the maximum bending moment on the cantilever. The vertical reaction at the wall is equal to W, and the wall must also be capable of resisting the bending moment W. L.

3.3.2. DEFLECTION OF CANTILEVER SPRING (Salmon)(50). p85 In the following case it will be assumed that both E and I are constant. Consider a uniform cantilever spring, span L, loaded with concentrated load W at the free end (Figure 18). Let A be the origin and, consider any section K distant x from A. Let y be the deflection there. The bending moment at K is $M = W(L - x)$. From Equation (21)

$$\frac{d^2y}{dx^2} = \frac{M}{EI} - \frac{W}{EI}(L-x)$$

Integrating this, E, I being constant,

$$\frac{dy}{dx} = \frac{W}{EI}\left(Lx - \frac{x^2}{2}\right) + C1 \ldots\ldots \qquad (25)$$

At the origin, where $x = o$, the beam is horizontal, hence,

$\frac{dy}{dx} = o$, and $C_1 = o$. From Equation (25) the slope of the beam everywhere can be obtained. Integrate again,

$$y = \frac{W}{EI}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) + C_2$$

At the origin, where $x = o$, the deflection $y = o$ and hence $c_2 = 0$.

Therefore, $y = \frac{W}{EI}\left(\frac{Lx^2}{2} - \frac{x^3}{6}\right)$ .... (26)

This equation gives the deflection at any section K. The maximum deflection occurs at B where $x = L$.

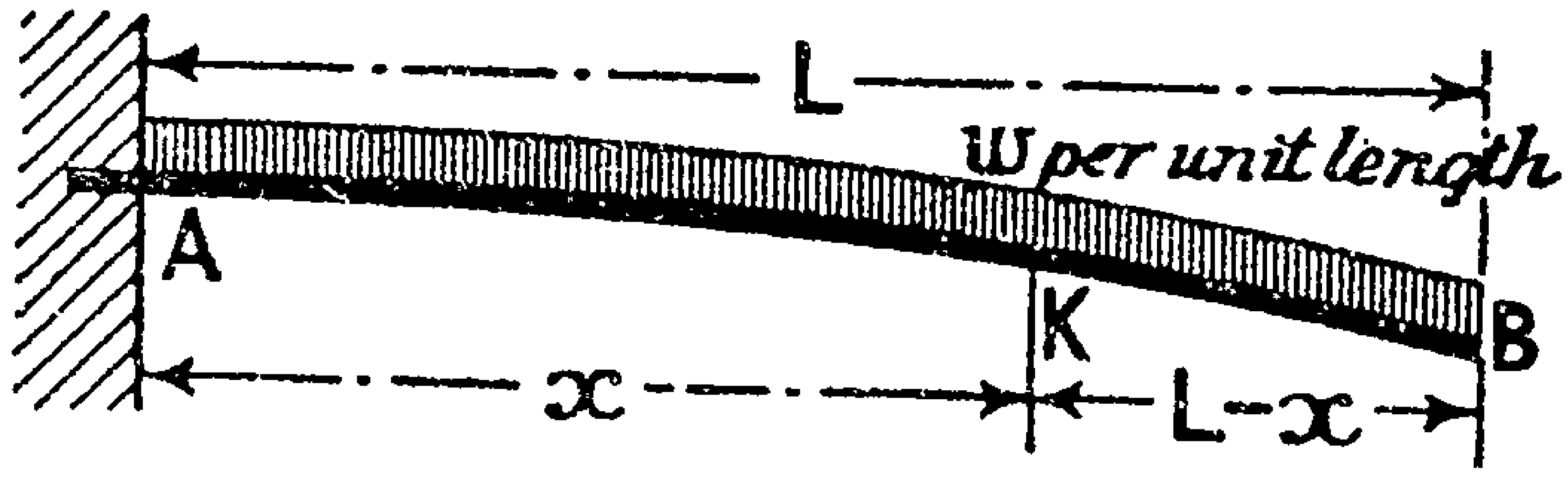


Figure 18. Deflection of a Cantilever Spring.

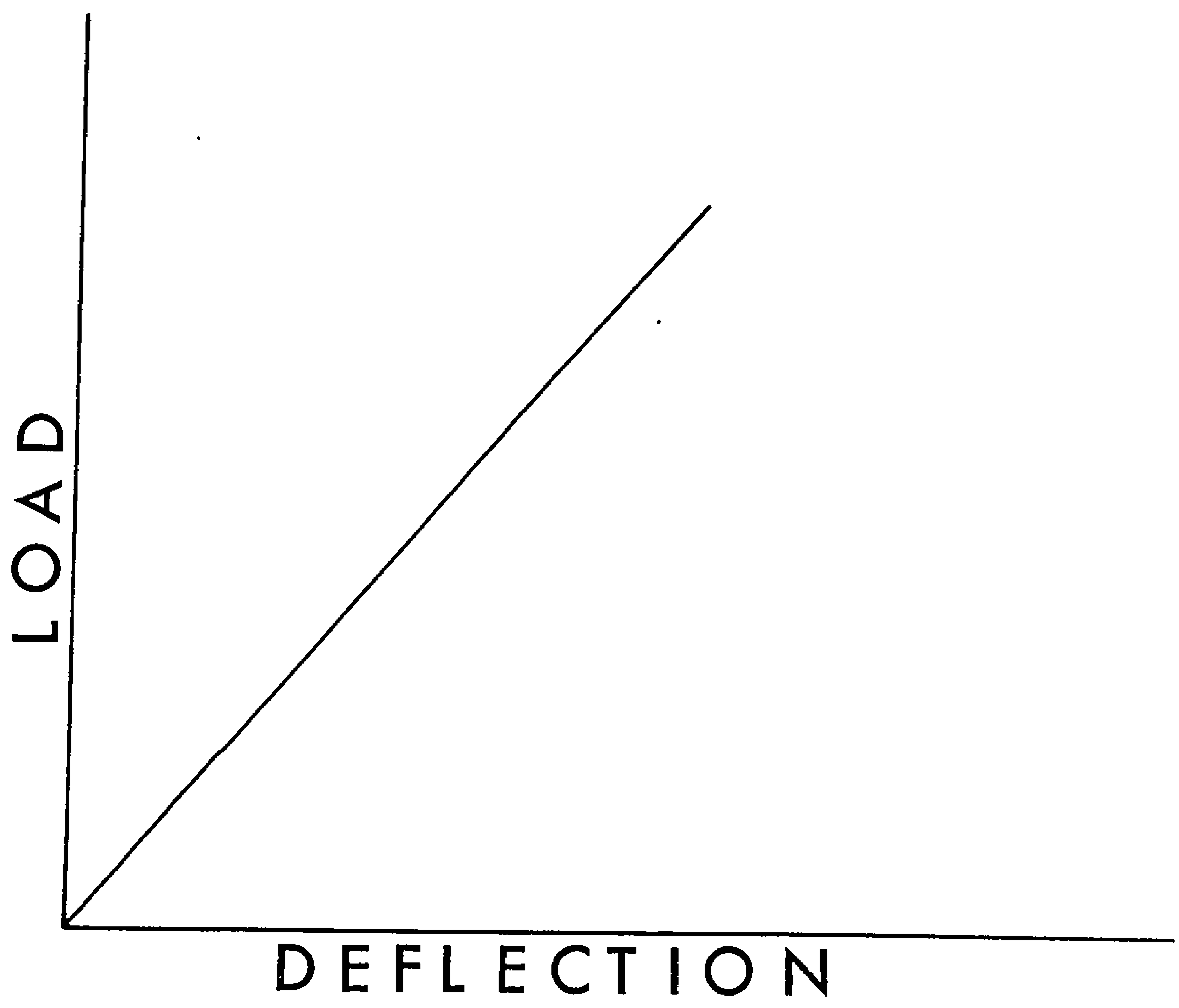


Figure 19. Linear Load-Deflection Curve of a Typical Spring.

$$\text{Max } y = \frac{W L^3}{3 E I} \qquad \text{.....................} \qquad (27)$$

The maximum bending moment which measures the strength is given as; Bromfield p 149

$$M = W L \qquad \text{.....................} \qquad (28)$$

The maximum stress in the beam is equal to

$$f = \frac{Mv}{I} \qquad \text{.....................} \qquad (29)$$

where M is the bending moment and $\frac{I}{v}$ is the section modulus of the beam, and the distance from the neutral axis to the most remote edge of the section is v. In the case of a circle or other sections whose gravity axis lie at the centre, v is half the depth. The equation for flexibility of a cantilever beam may then be re-written as follows

$$\text{Max.}y = WL \frac{L^2}{3EI} \frac{v}{v} = \frac{Mv}{I} \frac{L^2}{3Ev} = \frac{FL^2}{3EI} = K \frac{FL^2}{Ev} \text{........} \qquad (30)$$

The flexibility of this beam is equal to the product of a constant, the greatest unit stress in the beam, the square of the span length, divided by the product of the modulus of elasticity of the material and half the depth. Except for the constant K, which depends on the characters of the loads and supports, the flexibilities in bending of all structures have the same mathematical form. Flexibility varies directly as the greatest stress in the structure, which would have a limiting value equal to the proportional limit, and the square of the effective length in bending. It varies inversely as the modulus of elasticity of the material times the depth of the structure.

Consider the flexibilities and strengths of two structures 1 and 2, of the same general form, same lengths of structure in bending but of different materials and of different cross section perpendicular to the plane of bending.

From Equation (22)

Maximum $y_1 = \dfrac{K_1\ f_{p1}}{E_1\ V_1}$ and maximum $y_2 = \dfrac{K_2\ f_{p2}}{E_2\ V_2}$

If the loads are identical and both structures are of same general form $K_1 = K_2$, and if both are to have the same flexibility,

$$\text{then,} \quad \frac{f_{p_1}}{E_1 v_1} = \frac{f_{P2}}{E_2 v_2} \quad \dots\dots\dots\dots\dots\dots \quad (31)$$

for a circular section $v = \frac{d}{2}$ (where d is the diameter of the circular section)

$$\text{then,} \quad \frac{f_{P_1}}{E_1 d_1} = \frac{f_{P_2}}{E_2 d_2} \quad \dots\dots\dots\dots\dots\dots \quad (32)$$

If the two structures are to have the same strengths, then from Equation (23)

$$W_1 = K\ f_{P_1}\ \frac{I_1}{v_1} \quad \text{and} \quad W_2 = K\ f_{P2}\ \frac{I_2}{v_2}$$

Now, if $W_1 = W_2$ (i.e. same strengths)

$$\text{then} \quad f_{P_1}\ \frac{I_1}{v_1} = f_{P_2}\ \frac{I_2}{v_2} \quad \dots\dots\dots\dots\dots\dots \quad (33)$$

for a circular section $\frac{I}{v} = \frac{d^3}{32}$ (Salmon)[50]

$$\text{then} \quad f_{P_1}\ d_1^{\ 3} = f_{P_2}\ d_2^{\ 3} \quad \dots\dots\dots\dots\dots\dots \quad (34)$$

CHAPTER 4

GENERAL CONSIDERATIONS IN ORTHODONTIC SPRING DESIGN.

The first criterion for wire usage is the capability of delivering a specific amount of force. Several studies have been made of the amount of force required for specific tooth movements, Storey and Smith[57] have reported the optimum range of force for retraction of the lower cuspid is between 150-250 grams. Burstone and Groves[13] retracted anterior teeth by simple tipping and stated optimum rates of tooth movement were observed when 50-75 grams of force were applied. Reitan[42] has stated that the maximum force needed during any stage of a continuous bodily movement of canines is 250 grams. Reitan[43] also observed tooth movement by tipping when a force of 50 grams was applied.

Wahl[65] defines a mechanical spring as an elastic body whose primary function is to deflect or distort under load and which recovers its original shape when released after being distorted. Provided that the material is not stressed beyond the proportional limit, the usual type of spring will have a straight-line load deflection diagram as shown in Figure 19, provided geometry does not change during deformation. This means that the deflection is proportional to the load, i.e., if the load is doubled the deflection will be doubled. The relation will hold true even if the acting load is a torque or moment, provided linear deflection is replaced by angular deflection.

The forces used in orthodontic appliances have their origin primarily in elastically deformed wires. Since orthodontists are concerned with the "elastic" or "spring" properties of wire, it is desirable to refer to such mechanisms simply as orthodontic springs. Orthodontic springs may take advantage of either the bending or torsional properties of a wire. A finger spring and a vertical loop are examples of force derived from bending a wire. In a coiled extension or compression spring or a third order bend (torque) in an edgewise archwire, the force is obtained from the twisting or torsional properties of the wire. In order to design and utilize springs for orthodontic appliances, three spring characteristics must be considered (Burstone)[14]. They are:-

1. The relationship between load and deflection.
2. The load at which permanent deformation occurs.
3. The range of activation within the elastic limit.

The deflection at which permanent deformation occurs is described by Hooke's law which can be interpreted as stating that within the proportional limit of any material deflection is proportional to load. Hence, throughout the range of action of a spring, the quotient of applied force divided by deflection is constant. This constant is termed the spring constant, spring-rate or the load-deflection rate, and is usually given as grams per millimetre or gram millimetres per radian. Haack[27] designated the ratio of force to deformation the "stiffness". It represents the load necessary to produce a unit deflection. Load-deflection rates vary considerably in commonly - used orthodontic appliances and in some applications the load-deflection rate may vary in a given spring particularly if large deflections are employed. (Burstone[14], Wahl[65]). This is not a contradiction of Hooke's Law, but reflects the changes in spring configuration that occur during loading. This probably involves combined bending and torsion instead of simple bending and torsion. Since these springs lack a linear relationship of load and deflection, an average rate may be used to describe the force gradient. For greater accuracy, however, a table or graph showing the force per unit of activation is preferable to predicting the force on the basis of an average spring constant. If successive loads are placed on a spring, a point is reached at which permanent deformation will occur. The greatest load that can be applied safely to a wire without permanent deformation is the "proof load" and it is determined usually both by theoretical calculations and experimental data. The largest force placed on a member during a given action is the final load. In order to minimize accidental permanent deformation in springs, it is desirable to apply a final load that is considerably less than the proof load. Closely related to the proof load is the range of action per static loading. The range of action is the greatest distance through which a flexible member can be deflected without permanent deformation. Springs that have high proof loads and low-load deflection rates have high ranges of action. The desirability of continuous force in orthodontics may be questioned if high load-deflection rates are employed. A high spring-rate acting continuously between appointments will demonstrate a marked lack of uniformity in force magnitude. For this reason, appliances of this type must be activated so that the final load is great enough to ensure an average force level which is adequate for tooth movement. Physiologically, the final load is apt to be too large and hence, undesirable changes in the periodontium may follow.

The ideal orthodontic spring would have the ability to release a constant force throughout the entire range of its activation. This is not to imply that force levels should remain constant during a given range of tooth movement, but rather that sudden changes in force magnitude should be eliminated. Since Hooke's Law indicates that no spring is constant in its action, the request for a constant force spring resolves itself into the utilizatiion of springs with low load-deflection rates. In these terms a constant-force spring is one that approaches a zero rate. With a low spring rate it is necessary, however, to assume a sufficiently high proof load to prevent permanent deformation before reaching the final load. It can be seen that the design of relatively constant-force springs requires the development of flexible members that have both low rates and high maximum working loads. Mechanisms of this type are characterised by long ranges of activation and the ability to absorb considerable energy.

CHAPTER 5

FACTORS INFLUENCING ORTHODONTIC SPRING DESIGN

5.1. MECHANICAL PROPERTIES OF WIRE

The mechanical properties of the wire used in an orthodontic spring may alter both the rate and proof load of the spring.

From Equation 21

$$\frac{d^2y}{dx^2} = \frac{M}{EI}$$

and $M \propto W.L.$

$$\text{then } \frac{W}{y} \propto \frac{EI}{L}$$

For any given spring $\frac{I}{L}$ is a constant therefore spring rate $\frac{W}{y}$ is directly proportional to the modulus of elasticity. The modulus of elasticity represents a stress-strain ratio in compression or tension which expresses a measure of stiffness of a material. It is basically a constant for most wires but with some wires it can be altered quite significantly by heat treatment or work hardening. (i.e. cobalt chromium wire after heat treatment, work hardening, Mutchler[39].) If spring configuration and dimension remain unchanged, rate may be altered only by using various alloys with differing moduli of elasticity. (See Table 1.) If we compared similar springs of the two materials listed in Table 1, the steel spring would deliver more force for each millimeter of action than the gold spring, but the gold spring would have a range of action approximately twice that of the steel spring.

TABLE 1

COMPARISON OF MECHANICAL PROPERTIES OF TYPICAL GOLD AND STAINLESS STEEL WIRE (ANDERSON)[2]

	Gold Alloy Wire 10-20% Pt. and Pd.		18-8 Stainless Steel
	Annealed	Heat Hardened	Hard Drawn Wire
Proportional Limit $(Kg/mm)^2$	50	74	145
Tensile Strength $(Kg/mm)^2$	70	105	175
Modulus of Elasticity $(Kg/mm)^2$	11,000	11,000	23,000
Elongation (per cent)	20	6	1
B.H.N.	180	260	350

The mechanical property of an alloy that determines proof load is the proportional limit. Provided that the maximum stress in the cross section does not exceed the proportional limit of the material the beam or spring will behave elastically. The higher the proportional limit the greater is the proof load. Proportional limit can be affected markedly by composition, grain size, cold working and heat treatment. (Skinner)[53], (Metals Handbook)[(36)]. Cold working increases the yield strength of wire (Metals Handbook)[(36)] and since smaller diameter wires usually are subjected to greater cold working they will tend to have a higher proportional limit than larger diameter wires. (Wilkinson)[(68)].

Heat treatment further increases the proportional limit of some wires. (Metals Handbook)[(36)]. Burstone [(28)] considered that not all residual stresses are undesirable, for in many instances if these stresses are properly orientated they may increase the proportional limit. He believed that confusion sometimes exists in relating resistance to permanent deformation and the rate of a spring. On the basis of "feel", a clinician may believe that a spring made of soft steel wire has a lower spring rate than an identical spring fabricated of hard steel. It should be remembered that modulus of elasticity is approximately constant for a given steel alloy and, therefore, that the rates of identical soft and hard steel wire springs are nearly the same. The difference in "feel" can be explained by the higher proportional limit of the hard wire which requires a greater total force to produce permanent deformation.

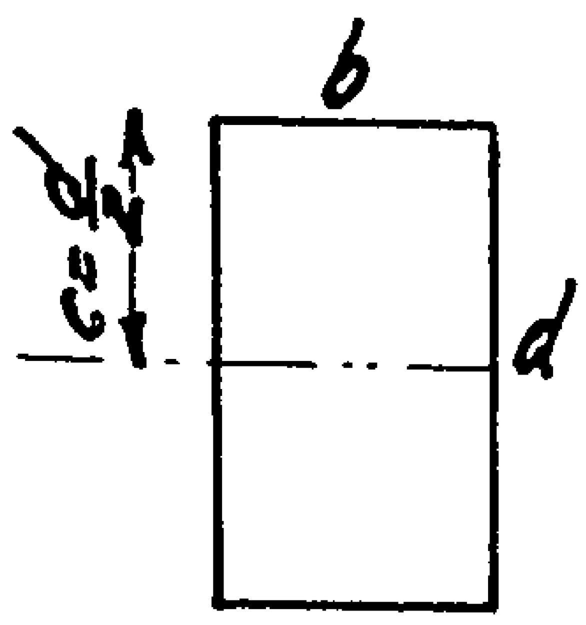
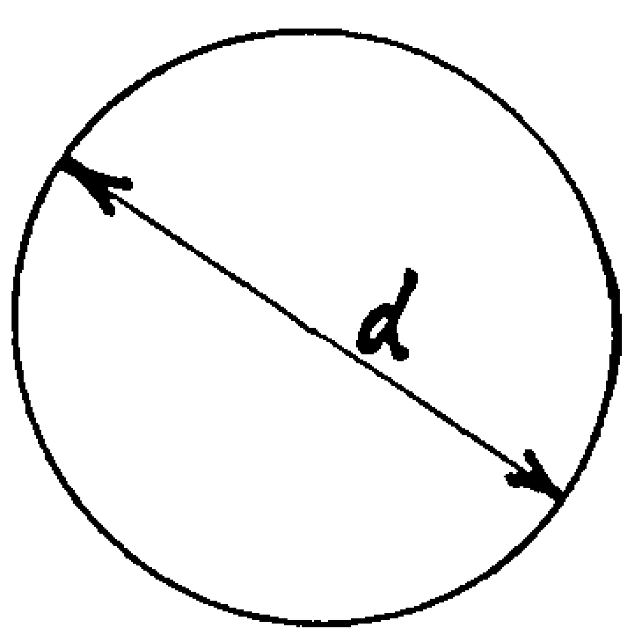
5.2. CROSS SECTIONAL GEOMETRY OF ORTHODONTIC WIRES.

The change in rate which occurs as a result of altering the cross section of a spring wire is not simply proportional to the change in the wire dimension or to the cross sectional area. The resistance of a wire to bending and hence, its rate, is determined by the distribution of the material around the neutral axis. (See section on Deflection of Beams, 2.4.)

It can be demonstrated that a relatively small increase or decrease in the cross section of a wire may result in a marked increase or decrease in the load deflection rate of an orthodontic spring. Specifically for round wire the spring rate increases as the fourth power of the diameter of the cross section. (Fig. 20). For instance, if a 0.020 in. wire and a 0.040 in. wire are deflected the same distance, the 0.040 in. wire exerts sixteen times as much force as the 0.020 in. wire although the diameter of the 0.040 in. wire is only twice as great. For square or rectangular wires (Figure 20) the spring rate is only directly proportional to the width, b, of the cross section but increases as the cube of the depth h. Thus a change in depth has a much more pronounced effect on the amount of force required for a given deflection than does a change in the width of the cross

Figure 20.

CHARACTERISTICS—BEAM SECTIONS

	Moment of Inertia	Section Modulus
	$I = \frac{bd^3}{12}$	$\frac{I}{c} = \frac{bd^2}{6}$
	$I = \frac{\pi d^4}{64}$ - Bending $I_T = \frac{\pi d^4}{32}$ - Torsion	$\frac{I}{c} = \frac{\pi d^3}{32}$ - Bending $\frac{I}{c} = \frac{\pi d^3}{16}$ - Torsion

section. For instance, the result of decreasing the depth by half is to reduce the spring rate by a factor of eight, but, if the width is decreased by the same amount the rate is reduced by a factor of two.

A low rate spring could be designed simply by reducing the dimensions of the wire cross section. However, this approach is limited by the fact that the proof load changes as the third power of the diameter in round wires, and as the breadth times the second power of the depth in rectangular wire. If the dimensions of the cross section are reduced too radically, the resultant decrease in maximum load may result in permanent deformations of a spring during its normal use. For example an 0.040 in. wire spring can withstand elastically approximately eight times as much loading as an 0.020 in. wire spring of the same design and alloy. Similarly an 0.010 in. x 0.020 in. rectangular wire can withstand elastically, only one eighth of the load supported by an 0.020 x 0.020 wire.

The optimal cross-sectional shape is determined by the loading conditions to which a spring is subjected. If a wire is to be bent in many directions during normal use, a round cross-section is desirable. The most advantageous cross section for unidirectional bending is flat wire. If two similar flexible members, except for cross-section, can support identical maximum loads, it is found that their rates vary as their diameters (round wires) or breadths and depths (rectangular wires). The rates vary as the distance from the neutral axis to the most remote fibre in the plane of bending. As an example, a cantilever spring fabricated from 0.023 in. diameter round wire and a similar spring of an 0.008 x 0.20 rectangular wire of the same material may be compared since the maximum loads for both springs are (almost) identical. By calculation the0.028 in. round wire has a rate three times as great as the flat wire spring.

5.3. WIRE CONFIGURATION OF ORTHODONTIC SPRINGS

Burstone[14], Jarabak[31], Smith and Storey[58], show that modification of the linear configuration can offer potential in altering the rate and proof load of a spring. They give examples of the effect of wire length, incorporation of helixes and spring design on the rate and proof load of a spring. Since the possibilities of design are numerous, consider a cantilever and assume that the load W is always applied at a right angle to the long axis of the wire in the plane of bending, throughout the range of action. A change in length of a cantilever produces a more dramatic effect on rate than on proof load.

From Equation (22)

$$\text{for a cantilever maximum deflection} = \frac{WL^3 64}{3E\ d^4}$$

specifically the rate varies inversely as the cube of the length

From Equation (23)

$$\text{for a cantilever maximum load} = \frac{Fp\pi d^3}{32L}$$

and the proof load varies inversely as the first power of the length. The effect of wire length can be illustrated by comparing a 10 mm. and a 20 mm. cantilever spring fabricated from the same wire. In respect of rate, the 10 mm. spring has a gradient eight times as great as the 20 mm. one. Yet the allowable load is only twice as high for the 10 mm. cantilever.

Modification of a cantilever along its length by the placement of coils or loops reduces spring rate without affecting proof load.

Although bends may be placed anywhere along the length of wire, the optimum position for the incorporation of additional wire is where the bending moment is maximal. Since the bending moment is directly related to the degree of bending at any cross section of wire, the greatest elastic deformation will occur where the bending moment is greatest. It is at this point that additional wire most effectively reduces the load deflection rate. The maximal bending moment of a cantilever loaded with a single transverse force is at its fixed end which is most remote from the point of force application. The incorporation of a helix in the area of maximum bending decreases the spring rate without significantly altering the ability of the spring to withstand permanent deformation.

Burstone[14] gives the spring rate in a cantilever spring modified with a helix as being determined by the diameter of the helix, number of turns in the helix and the length of the cantilever.

$$\frac{W}{D} = \frac{E\,I}{2\,r\pi n\,(L^2 + \frac{r^2}{2}) + 4L\,r^2 + \frac{L^3}{3}}$$

where E = modulus of elasticity

I = moment of inertia

n = number of turns in helix

L = length of arm

r = radius of helix

$\frac{W}{D}$ = load deflection rate

For example, if a 10 mm. cantilever is compared to a cantilever (of the same wire) with one turn in a 3 m.m. helix, it is found that the rate of the modified cantilever is reduced to about one half (forty six per cent). On the other hand, if two turns are placed in the helix the rate dimished by fifty eight per cent.

The elimination of sharp bends enhances the elastic properties of a spring. If a bend is acute, stress concentration will occur at this point and permanent deformation is more likely to result when the wire is loaded. This danger is greatest where the bending moment is maximum and it is here that acute bends should be particularly avoided. Burstone(14) concludes that:-

1. Load/deflection rates can be lowered by reducing the cross-sectional area.
2. The greatest potential in altering spring properties is found in the linear configuration. The placement of

additional wire where the bending moment is maximal lowers the rate without changing the maximum load that may be sustained without permanent deformation.

3. Although the mechanical properties of a wire partly determine its action, the primary factor in the delivery of continuous force is the design of the spring.

CHAPTER 6

MATERIALS

6.1. STAINLESS STEEL

Rust resisting iron-chromium alloys were discovered by Brearley in 1913, and developed by Strauss and Maurer in Germany in 1913 (Monypenny)[38], but probably were not generally available until around 1919 and were introduced in the orthodontic field in the United States around 1929 or 1930 (Gaston)[25]. De Coster[18] (1932) reported that stainless steel had been used for orthodontic purposes in Belgium since 1924.

The material in which we are primarily interested in orthodontics is A.I.S.I. type 302, which contains (in addition to the iron content) the following chemicals: carbon .15% maximum; manganese 2% maximum; silicon 1% maximum; chromium 17-19%; nickel 8-10%. Another alloy which is very similar to this, and has almost identical physical properties is type 304, the main difference between the two being that 304 contains only 0.08% carbon maximum, and from 18-20% chromium and 8-12% nickel. These alloys are austenitic, very high in corrosion resistance, non-magnetic when annealed but slightly magnetic when cold worked (Gaston)[25].

American workers found this material difficult to solder, initially, because the fluxes used could not dissolve the outer surface oxides. When this problem was overcome, it was found that joints of excellent appearance discoloured and broke apart after two to ten weeks in the mouth. (Gaston)[25], (Brusse and Carmen)[12], (Bell)[5]. Even in 1951 Gaston[25] wrote of the technique of spot welding before soldering to overcome the difficulty of wires sliding out of the enveloping solder, although this difficulty is not present today.

Spot welding was probably introduced about 1930 in Europe (De Coster)[18] and about 1933 in the United States (Walsh)[66]. Simon[51] in 1922 described the use of tin solders for stainless steel in orthodontics which suggests that Europeans were in difficulty with soldering these alloys. By 1933 chrome alloy wires were being used successfully by a numbers of workers in the United States (Gaston)[25]. However as late as 1937 widely differing opinions of the relative merits of soldering and spot welding were expressed, even though Vosmik and Taylor[62] in 1933 had demonstrated the benefits of silver solders (without explicitly examining the tendency for joints to break).

The suitability of stainless steel wires for orthodontic appliances is primarily due to the following properties:-

1. Great strength.
2. High modulus of elasticity.
3. Resistance to corrosion in the mouth.
4. Low cost as compared to precious metal alloys.

6.1.1. GENERAL CONSIDERATION OF HARD DRAWN STAINLESS STEEL ARCH WIRE. (Wilkinson)[68]. In the annealed state austenitic steel consists of roughly equiaxed grains. High tensile strength and high proportional limit can be induced in these steels by plastic deformation below the recrystallisation temperature. The finer the grain size before cold working, the greater will be the improvement in the mechanical properties. Grain size can be reduced by alternate plastic deformation and recrystallisation. In manufacturing practice, a wire is drawn down to size in stages. The drawing process distorts the grains into tiny fibrous shapes, elongated along the length of the wire. When softening is required the wire is heated to a temperature which will cause recrystallisation of the metal. The process of recrystallisation is governed mainly by two factors - temperature and time. The higher the temperature the faster the rate of recrystallisation. Second, the time factor affects the size of the grains; once recrystallisation has occurred, prolonged heating causes growth in size of the grains. This will change a fine-grained structure to a coarse-grained structure and consequently the metal will become softer.

6.1.2. EFFECT OF HEAT ON MECHANICAL PROPERTIES OF STAINLESS STEEL ORTHODONTIC WIRE. It is a generally accepted fact that the elastic properties of formed orthodontic arch wire are improved by low-temperature heat treatment at 300 - 500^{0} C for a short period. (Backofen and Gales)[(4)], (Howe et al)[(29)], (Ingerslev)[(30)]. This procedure is often referred to as hardening, stress relieving or, simply as heat treatment.

Its effect has been the subject of investigation at frequent intervals throughout the last few years.

In experiments in which wires, bent in a series of V-shapes were heat treated and subjected to tension, Funk[24] found a marked improvement in the elastic properties, no such improvement was observed for treated straight wires subject to deflection.

Backofen and Gales[4] who studied the expansion of U-shaped loops under tension, found a marked increase in the elastic strength after heat treatment.

Kemler[32] concluded from an experiment on the expansion of uniform round loops of stainless steel that a low temperature heat treatment resulted in an increase in the proportional limit and elastic modulus.

In experiments on the proportional limit, tensile strength and hardness of austenitic stainless steel, Wilkinson[67] found that the properties depended on the period of heat treatment and the temperature, and that annealing of the wire starts at 500° C and since clinically satisfactory low-fusing solder melts in the range $650 - 750^{\circ}$ C, some softening must be expected when wire is soldered. He also found that for the range of temperatures and times selected, the hardness of the particular wire tested was directly proportional to its tensile strength.

Using 18-8 stainless steel wire coiled around a cylinder, Mutchler[39] showed that heat treatment resulted in changes in proportional limit and the modulus of elasticity.

Delgardo and Anderson[19] considered that the effect of low temperature heat treatment of 18-8 stainless steel, on tensile strength and capacity for bending is not great enough to be of use in clinical practice.

Ingerslev[30] in a series of experiments on formed archwires of 18-8 stainless steel found that heat treatment produced changes in elastic limit for expansion and compression of the arches and for deflection of straight segments of the same wire. He considers that changes in the elastic limit are due to resolution of the internal stresses introduced during the cold working of the wire and that archwires of the 18-8 stainless steel used should not be heated at 400°C or more as this considerably reduces the resistance to corrosion. The modulus of elasticity was not affected by the time-temperature combination used.

6.1.3. EXPERIMENTAL WIRE. The stainless steel wire used for experimental work was Remanit Dentaurum "spring hard", from the Dentaurum Company, Pforzheim, West Germany. The wire was purchased from the local agent. The manufacturer's catalogue[20] describes these wires as "being made from fine quality stainless steel, absolutely mouth acid-resistant and of outstanding tensile and yield strength and are highly resilient". The only figure quoted for this wire is that for ultimate tensile strength, being 270 - 285 P.S.I.

A tensile test was carried out on straight lengths of this wire after being heat treated, using a Hounsfield Tensometer and two opposed Huggenburger strain gauges. The results were:-

Remanit Stainless Steel Wire (Spring Hard)

0.0385" diameter

Heat treated in a 3" diameter tube furnace for 10 minutes at 405° C.

Five tests

0.02% proof stress 190,000 $\pm$ 3.5% p.s.i.

(one high value disregarded)

Ultimate Tensile Strength

297,000 p.s.i. $^{+\,1.2\%}_{-\,0.6\%}$

Youngs Modulus

26.2×10^6 p.s.i. $^{+\,5.7\%}_{-\,3.8\%}$

6.2. COBALT CHROMIUM WIRE.

Relatively little comprehensive literature exists on the cobalt-nickel wire studied. The original manufacturer, the Elgin National Watch Company[59], of Elgin, Illinois, claims that their cobalt-nickel wire "Elgiloy", combines the excellent strength characteristics and corrosion resistance of cobalt, the added corrosion resistance of chromium, and the strength and ductility of nickel. Molybdenum is added to increase the mechanical properties at elevated temperatures while the remaining elements provide the additional properties of hardenability and set resistance. The nominal composition of "Elgiloy" is as follows:

Nominal Composition

Patented: U.S. Pat. No. 2524661

Cobalt	-	40%	Manganese	-	2%
Chromium	-	20%	Carbon	-	0.15%
Nickel	-	15%	Beryllium	-	0.04%
Molybdenum	-	7%	Iron	-	Balance

In application the manufacturer(59) claims the wire form of "Elgiloy" has demonstrated the following outstanding characteristics:

1. Less than 2% set as compared to 10% set for music wire in identical long term tests.
2. Hysterisis loss of less than 1/10 of 1% in torsion bar applications.
3. Less than 0.6% loss in load at 75,000 p.s.i. stress level at 575°F in compression spring test.
4. Superior resistance to corrosive attack.

It is claimed that a 45-48% cold reduction results in optimum spring temper. This decision is based on securing the best shear strength properties coupled with the ductility necessary for proper forming and maximum spring characteristics. To obtain maximum properties this cold reduction is usually combined with heat treatment at 980°F after forming. It is not a true precipitation hardening alloy since the amount of heat treatment is a function of the amount of cold work. Therefore, when "Elgiloy" is annealed, the cold work is removed and maximum properties cannot be regained by heat treatment. This combination of cold work and heat treatment will result in the following typical mechanical properties for "Elgiloy" wire.

Ultimate Strength	340,000 p.s.i.
Yield Strength	310,000 p.s.i.
Shear Yield	210,000 p.s.i.
Modulus of Elasticity	28,500,000 p.s.i.
Torsional Modulus	11,200,000 p.s.i.
Hardness (Rockwell C)	51-55

Four forms of this wire are listed by the supplied, Rocky Mountain Dental Products Company[41], of Denver Colorado. These are:-

1. R.M. Red High Spring Temper Elgiloy (Resilient)

   "Hard" wire with exceptionally high spring qualities. Not recommended for techniques involving sharp plier manipulation since it will only allow minimum work hardening.

2. R.M. Green Elgiloy (Semi-resilient).

   Spring temper is comparable to a good spring tempered steel wire. They can be shaped easily with fingers and allow for some plier manipulation before heat treating. However after heat treating they should not be adjusted sharply.

3. R.M. Yellow Elgiloy (Ductile).

   This is relatively ductile and can be bent with fingers and pliers. It is difficult to solder smaller yellow "Elgiloy" wires. They should be heat treated for maximum resiliency and performance and can be adjusted slightly after heat treating.

4. Blue Elgiloy(Soft).

   Soft and can be easily bent with fingers and pliers. Recommended when wire to be used is over 0.020" or when wire requires considerable shaping, welding or soldering. Should be heat treated for best results.

6.2.1. HEAT TREATMENT. The suppliers give the following information on how to heat treat "Elgiloy".

1. R.M. Heat-Treat Unit and Tempering Paste. Average heat-treat time is 30 seconds.
2. R.M. Adapting Cables. Place cable tips about $\frac{3}{4}$" apart on arch wire. Heat wire to straw colour. (Do not allow wire to become red hot, as this will anneal wire). Heat adjacent section and proceed along arch.
3. Brush Flame. Bring wire to deep red colour.
4. Dental Oven. $900^{\circ}F$ for 7 - 12 minutes.

Mutchler[39] investigated the effect of various time-temperature combinations on the mechanical properties of "Elgiloy" wire, and found that the wire is capable of exhibiting a significant improvement in its mechanical properties after heat treatment.

He concluded that:-

1) Controlled heat treatment produces an increase in the proportional limit, modulus of elasticity and modulus of resilience.

2) The optimum heat treatment for the cobalt chromium wire studied (Elgiloy) is 3 to 15 minutes at a temperature of 900°F (482°C) to 1000°F (538°C).

3) Prolonged heating has no significant effect on the wire studied.

4) Temperatures of 1100°F (593°C) and 1200°F (649°C) produce no harmful effect in the cobalt chromium wire when heated for less than 3 minutes.

He did not heat the wire above 1200°F (649°C) and made no comment on heating above this temperature. He found that in all cases the modulus of elasticity was increased by approximately 20% when heated to 900°F and considers that the increase is not due to work hardening alone, but probably to some type of crystalline rearrangement during heat treatment which results in intramolecular attraction and that the constitution of the alloy may be varied sufficiently to provide a group of alloys with a range of mechanical properties.

6.2.2. EXPERIMENTAL WIRE. Brockhurst[7] gives the following on "Elgiloy" yellow and "Elgiloy" blue.

"<u>Elgiloy"Yellow</u>. (See Fig. 21 for effect of heat treatment on yield point and ultimate strength, Fig. 22 for heat treatment, hardness.)

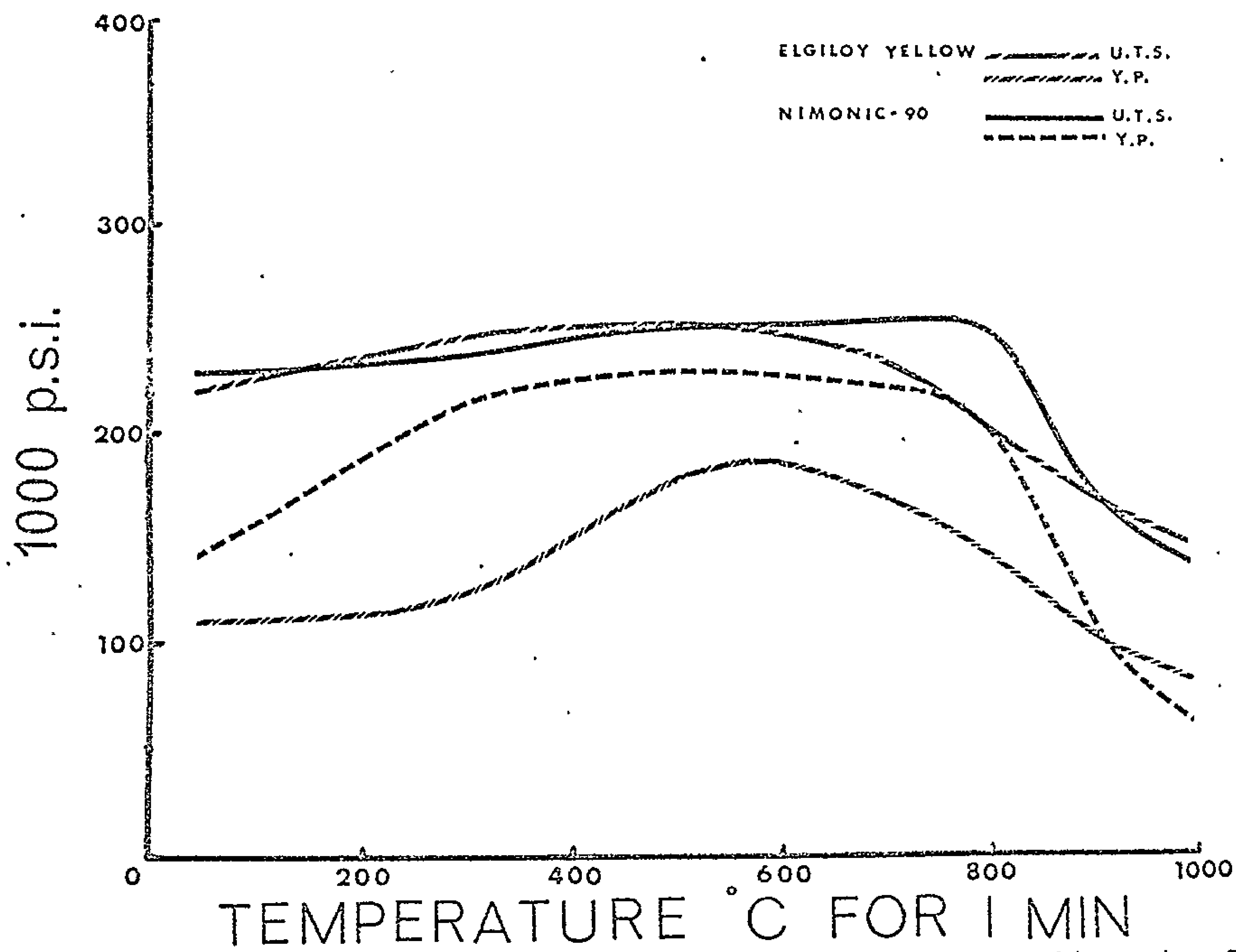


Figure 21.

Ultimate Tensile Strength and Yield Point after Heat Treatment of Cobalt Chromium (Yellow Elgiloy) and Nimonic 90 Wires.

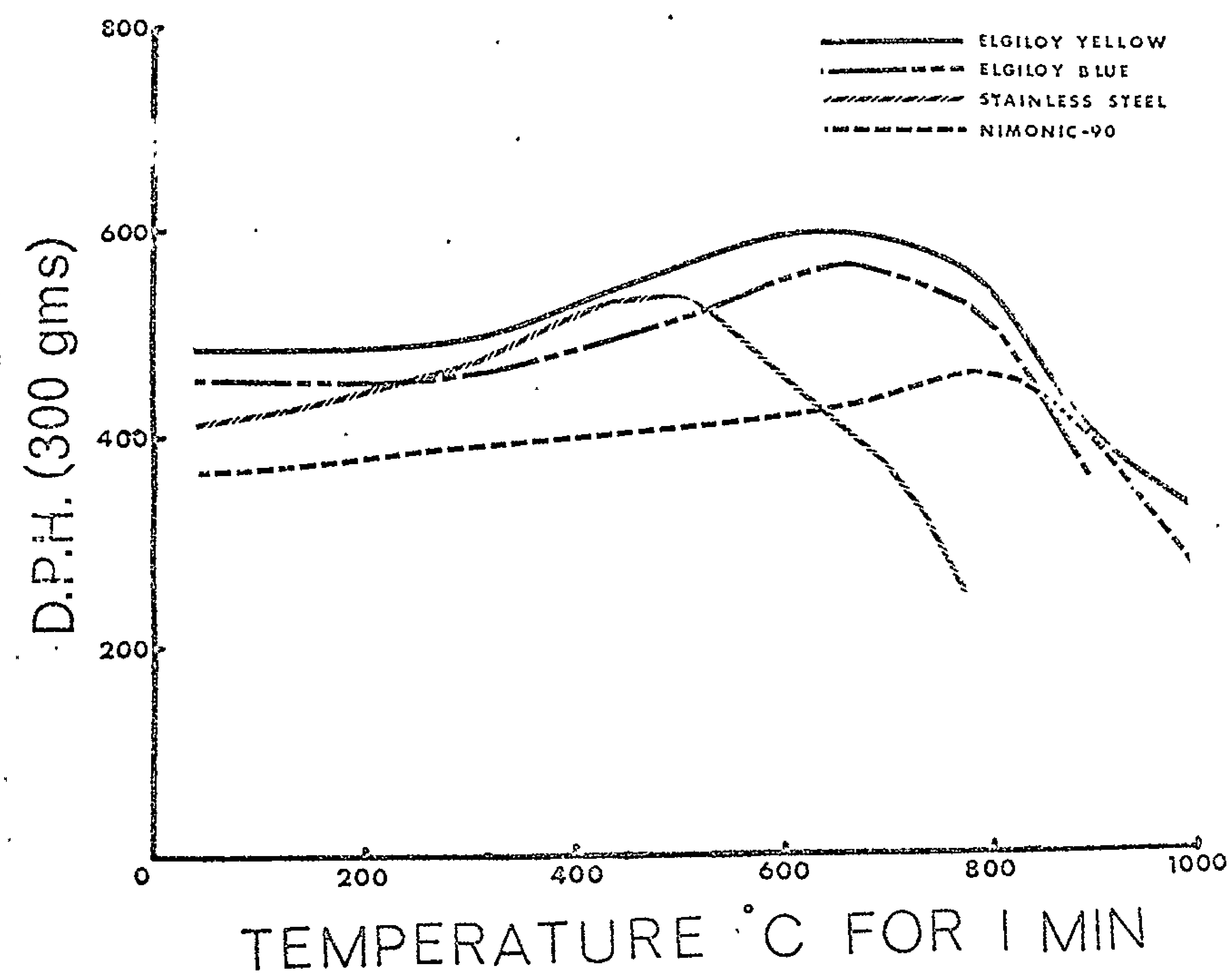


Figure 22.

Hardness (D.P.N.) V Temperature of Cobalt Chromium (Blue and Yellow Elgiloy), Stainless Steel and Nimonic 90 Wires.

Yield stress as received		111,000 p.s.i. 0.02% yield
	600°C for 1 min.	187,000 p.s.i.
Ultimate Tensile Strength		
	as received	228,000 p.s.i.
	600°C for 1 min.	246,000 p.s.i.
Vickers Microindentation Hardness Number		300 gm. load
	as received	484
	600°C for 1 min.	592

Mechanical properties decrease rapidly after 800°C.

"Elgiloy" Blue

Yield stress as received		98,000 p.s.i. 0.02% yield
Ultimate Tensile Strength		218,000 p.s.i.
Hardness D.P.N.	as received	450
	650°C for 1 min.	576

6.3. NIMONIC 90. The nickel base alloy used in experimental work, Nimonic 90, an alloy of the wrought, heat resisting group of alloys. No comprehensive dental literature exists on the nickel base alloy studied. Available data is related to high temperature performance only. (Metals Handbook)[37].

Nominal composition of Nimonic 90 alloy is (Metals Handbook)[37]:-

Carbon	0.1% max.
Manganese	1% max.
Silicon	1% max.
Chromium	20%

Nickel	Remainder
Cobalt	18%
Titanium	2.50%
Aluminium	1.5%
Iron	5% max.

Some of the other alloys in this group are Hastelloy, Inconel, Waspaloy. The alloys are manufactured in all forms common to the industry; billets, sheet, tubing and wire. The nickel base alloys have achieved wide acceptance in aircraft applications, largely as a result of their suitability at elevated temperatures. The alloys containing aluminium are hardened by a single or double ageing treatment, being cooled from the range 1750 to 2150°F. Yield strength of 110,000 p.s.i. and ultimate tensile strength of 175,000 p.s.i. at 75°F were obtained after a heat treatment of air cooling from 1975°F, reheating to 1300 F, then air cooling.

The nickel base alloys are welded and soldered by the same procedures as are used for the series 300 stainless steels.

The nickel base wire used in experiments was obtained as a sample from Wright and Company, of Sydney, and was manufactured by Henry Wiggin and Company, Birmingham, England. The manufacturer[28] states that Nimonic 90 spring wire is available in the cold drawn hard condition or in the solution-treated condition. Cold drawn hard wire is supplied with a bright finish; wire in the solution treated condition has an oxidized finish in sizes 0.104 in. diameter and larger, and a dull but clean finish in sizes below 0.104 in. diameter. Manufacturing procedures and mechanical properties are listed below (Tables 2 and 3).

For applications where severe cold forming is necessary, material in the solution treated condition should be specified, and after forming the components should be aged (4 hours 750°C).

6.3.1. EXPERIMENTAL WIRE. Brockhurst[7] gives the following information on the wire used experimentally (see Fig. 21 for effect of heat treatment on yield stress and ultimate tensile strength; Fig. 22 for hardness.)

Nimonic 90 wire 0.036" diam. solution treated 30% cold drawn

Yield Stress	As received	142,000 p.s.i.	0.02% yield
	800°C for 1 min.	216,000 p.s.i.	0.02% yield
Ultimate Tensile Strength			
	As received	220,000 p.s.i.	
	800°C for 1 min.	257,000 p.s.i.	
Microindentation hardness 300 gm. load			
	As received	363	
	800°C for 1 min.	470	

Mechanical properties decrease rapidly after 850°C.

6.4. PLATINISED GOLD WIRE.

Crowell[17] stated that orthodontic fabrications require high strength and resistance to corrosion in the mouth and that both

TABLE 2

Manufacturing Procedures - Nimonic 90 Springs			
Service Temperature° C	Recommended Wire Form	Heat Treatment After Coiling	Service Condition of Wire
Up to 350	Cold drawn hard spring temper	4 hours at 650°C air cooled	Direct-aged from cold-drawn
Above 350	Solution treated	4 hours at 750°C air cooled	Solution treated and aged

TABLE 3

Mechanical Properties - Nimonic 90 Spring Wire

	Solution Treated and Aged	Direct Aged from Cold Drawn
Modulus of elasticity in tension lb/sq.in. x 10^6 at $20^{\circ}C$	31	33 - 35
Limit of proportionality in tension lb/sq.in. x 10^3	72	130 - 140

requirements are met by the complex alloys based on gold and platinum. These alloys age-harden readily, and values for tensile strength and hardness may be obtained that are unusually high for non ferrous metals. The modulus of elasticity is of the order of 15 x 106 p.s.i. The composition limits in eight groups or types of modern dental gold alloy wires are given in Table 4, and some of the mechanical properties of these alloys are indicated in Table 5. Skinner[54] and Wise[70] described the nature of these alloys and their response to heat treatment. Wise[70] believed that the art of age-hardening alloys originated with the precious metals, as it was observed as early as 1905 by the S.S. White Dental Manufacturing Co., that a gold, platinum, silver, copper alloy would harden upon cooling from red heat.

Skinner[54] maintained that the directions of the manufacturer should be followed in heat treatment, particularly for age-hardening since the optional age-hardening temperature depends upon the composition of the alloy and it may be a narrow or broad range. He (Skinner)[55] gave details on the general effects of constituents in dental gold alloy wires.

Bush, Taylor and Peyton[15] compared the mechanical properties, chemical compositions and microstructures of dental gold wires. Some of their conclusions were:-

1. A definite correlation exists between the hardness and tensile strength of wrought gold alloys of varying chemical

TABLE 4.

Composition Limits of High-Strength Precious Metal Wires used in Dentistry*

Alloy	Composition (a)							Colour
	Au	Pt	Pd	Ag	Cu	Ni	Zn	
1.	25-30	40-50	25-30	-	-	-	-	Platinum
2.	54-60	14-18	1- 8	7-11	11-14	1 max.	2 max.	Platinum
3.	45-50	8-12	20-25	5- 8	7-12	-	1 max.	Platinum
4.	62-64	7-13	6 max.	9-16	7-14	2 max.	1 max.	Light Gold
5.	54-70	2- 7	5 max.	9-15	12-18	2 max.	1 max.	Gold
6.	56-63	5 max.	5 max.	14-25	11-18	3 max.	1 max.	Gold
7.	10-28	25 max.	20-37	6-30	14-21	2 max.	2 max.	Platinum
8.	-	1 max.	42-44	38-41	16-17	1 max.	-	Platinum

(a) Fractional Percentages of Iridium, Indium and Rhodium are omitted here.

* Metals Handbook 1964 Edition p.1188.

TABLE 5.

Some Physical and Mechanical Properties of High-Strength Precious Wires used in Dentistry*

Alloy (a)	Tensile Strength 1000 p.s.i.		Proportional Limit 1000 p.s.i.		Elongation % (8 in gauge)		B.H.N.(e)		Fusion Temp.
	Soft	Hardened	Soft	Hardened	Soft	Hardened	Soft	Hardened	Wire Method °F
1.	125-180	g	80-150	g	14-15	g	200-245	g	2730-2790
2.	110-130	160-186	72-102	130-151	12-22	5-10	150-190	240-285	1840-2010
3.	140-150	160-190	110-120	130-140	8-10	7- 9	210-230	250-270	1950-2050
4.	90-115	120-165	55-80	85-140	14-26	2- 8	166-195	240-295	1730-1860
5.	82-120	130-165	53-73	103-139	14-20	1- 3	135-200	230-290	1650-1710
6.	84-100	96-157	52-58	10-124	20-28	1- 2	138-170	220-280	1610-1650
7.	96-148	150-192	60-115	110-160	9-20	1- 8	150-225	180-270	1725-1975
8.	100-110	130-170	63-87	107-127	16-24	8-15	150-200	235-270	1980-1970

* Metals Handbook 1964 Edition p.1188.

(a) See Table 4 for chemical compositions of alloys.

(g) Not appreciably affected by Heat Treatment.

compositions.

2. A similar correlation exists between the proportional limits and tensile strengths of alloys which can be expressed as a ratio of the one to the other, for example, proportional limit equals 2/3 tensile strength.

3. A linear relationship exists between the proportional limit in bending and diamond pyramid hardness. A similar relationship exists between proportional limit in bending and ultimate tensile strength.

6.4.1. EXPERIMENTAL WIRE. The precious metal wire used experimentally was a Type 2 alloy (Table 4), Ney-Oro Elastic 12, manufactured by the J.M. Ney Company, Maplewood Ave., Bloomfield, Conn., U.S.A. and purchased from a local dental supply house.

The manufacturer[60] gives the following physical properties for the wire chosen.

Ney Wire Oro Elastic No.12

Physical Properties	Fusion Temperature	2010°F.
	Soft	Hardened
Proportional Limit	88,000 p.s.i.	135,000 p.s.i.
Ultimate Tensile Strength	125,000 lb./sq.in.	178,000 lb./sq.in.
Elongation	20%	15%
Brinell Hardness Number (B.H.N.)	175	275
Specific Gravity	12.1 gm/cc.	

The wire is supplied from the factory fully annealed (manufacturers claim), having had all work hardness removed after the final drawing operation. "To produce sufficient hardness for most ordinary requirements, the appliance can simply be allowed to cool in the air after soldering." (Manufacturer)[60]. If a greater hardening effect is desired, it should be placed in a controlled furnace at 900°F and allowed to cool from that temperature to 450°F. in fifteen minutes.

CHAPTER 7.

METHOD

The experiments were carried out on the wires listed in Table 6, which were obtained from local (dental) suppliers, with the exception of the nickel base alloy which was supplied by courtesy of manufacturer's agent (Wright and Company Pty. Ltd., Alexandria, N.S.W.).

7.1. FABRICATION OF ARCHES

The wires were obtained in straight lengths with the exception of the Nimonic 90 and stainless steel wires which were in coil form. The wires were cut into 150 mm. lengths, and at one end of each length a round loop 2.5 to 3.5 mm. in diameter was bent using loop forming pliers. To obtain a shape comparable with a finished orthodontic upper lingual expansion arch, a standard arch former was used (Figures 23 and 24).

The end loop was placed over a fixed pin (P. Figure 24) and the wire placed so that it rested in a horizontal groove in a stationary cylinder (I. Figure 24). On top of this was then placed a rotating tube part with a vertical pin to keep the wire in the groove; when rotating this top part of the arch former the wire was carried around the groove so that the straight length of wire remaining rested along the straight line C D. (Figure 24). The second stationary cylinder was then inserted in the

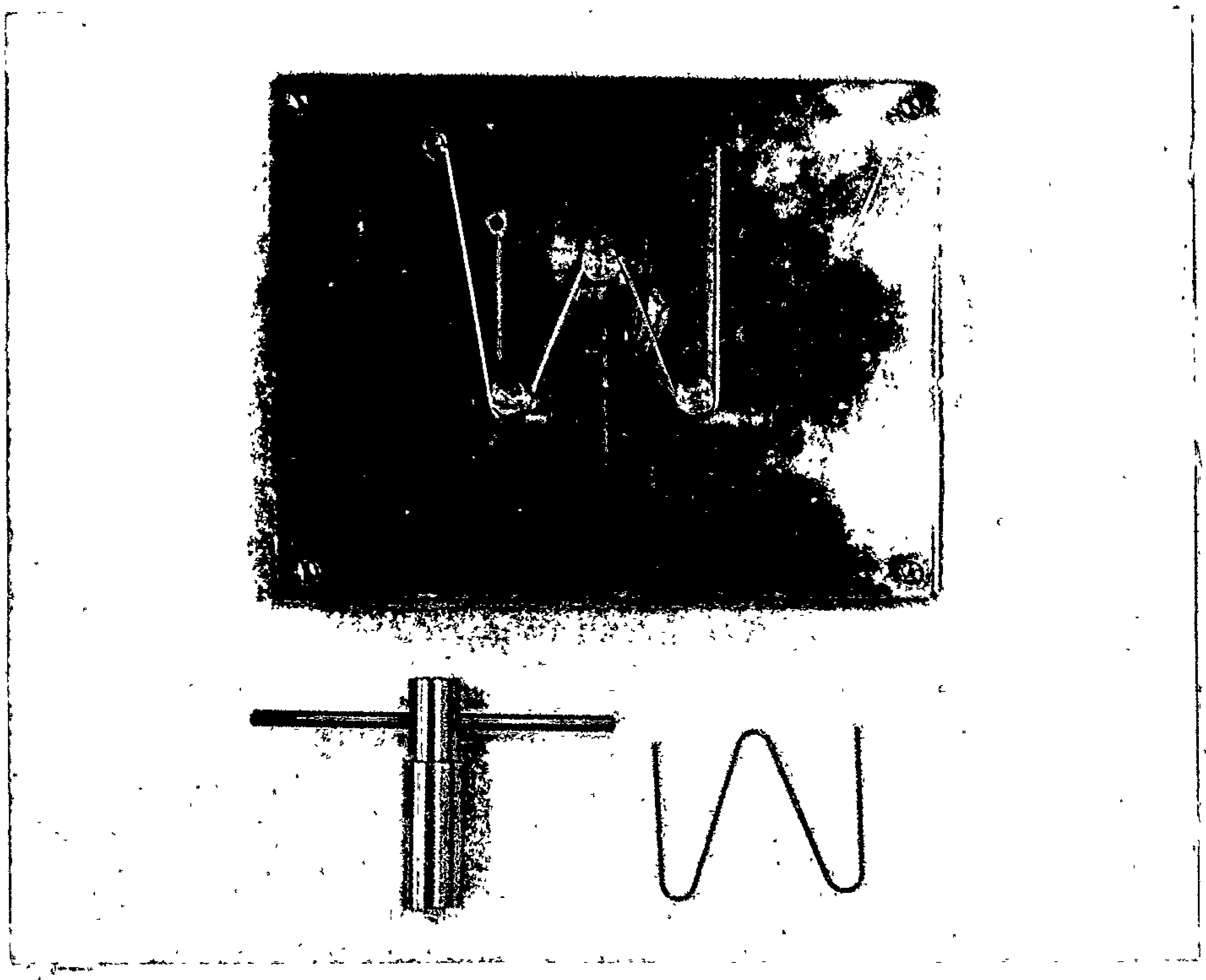


Figure 23.

Standard Arch Former

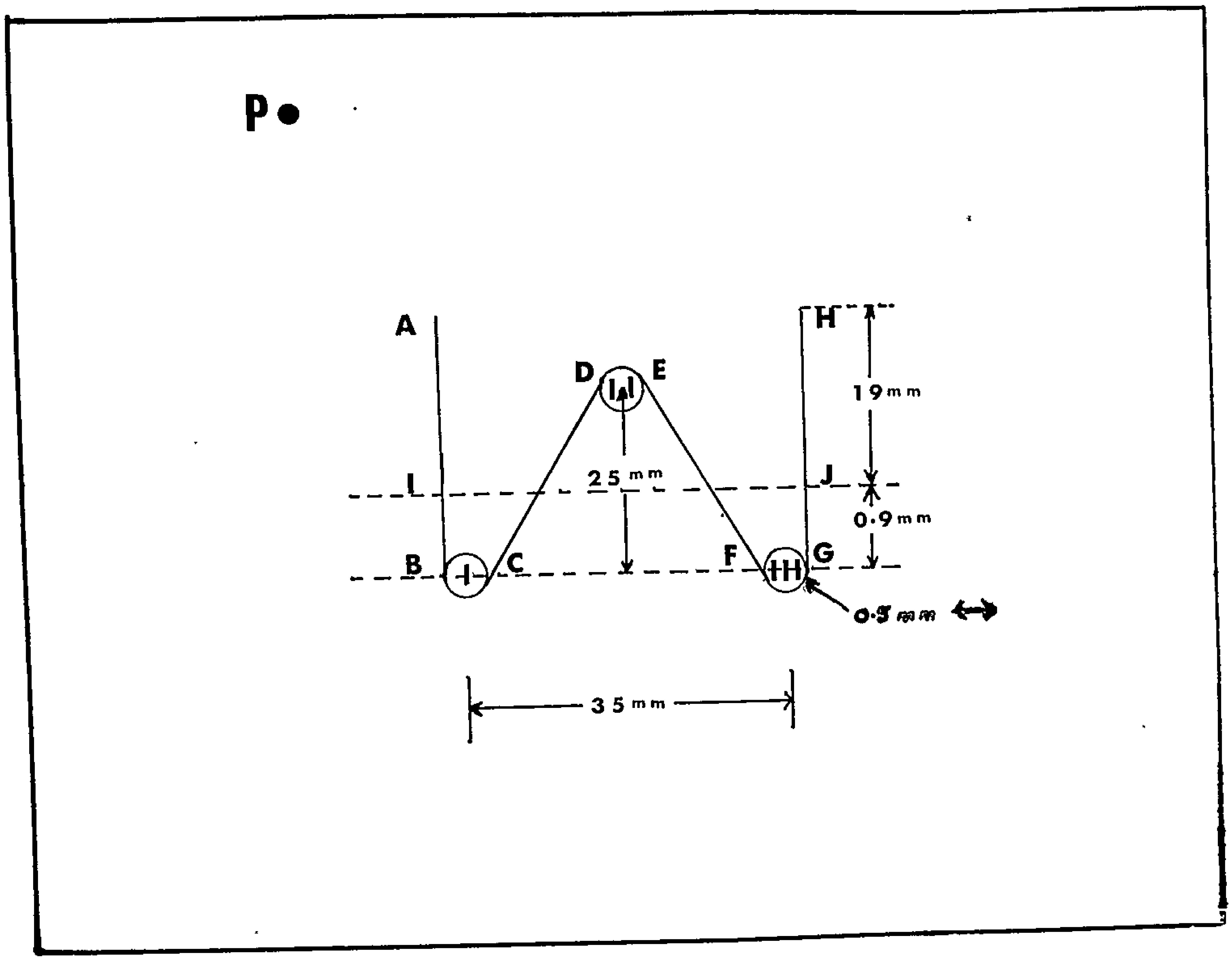


Figure 24. Dimensions Standard Arch Former.

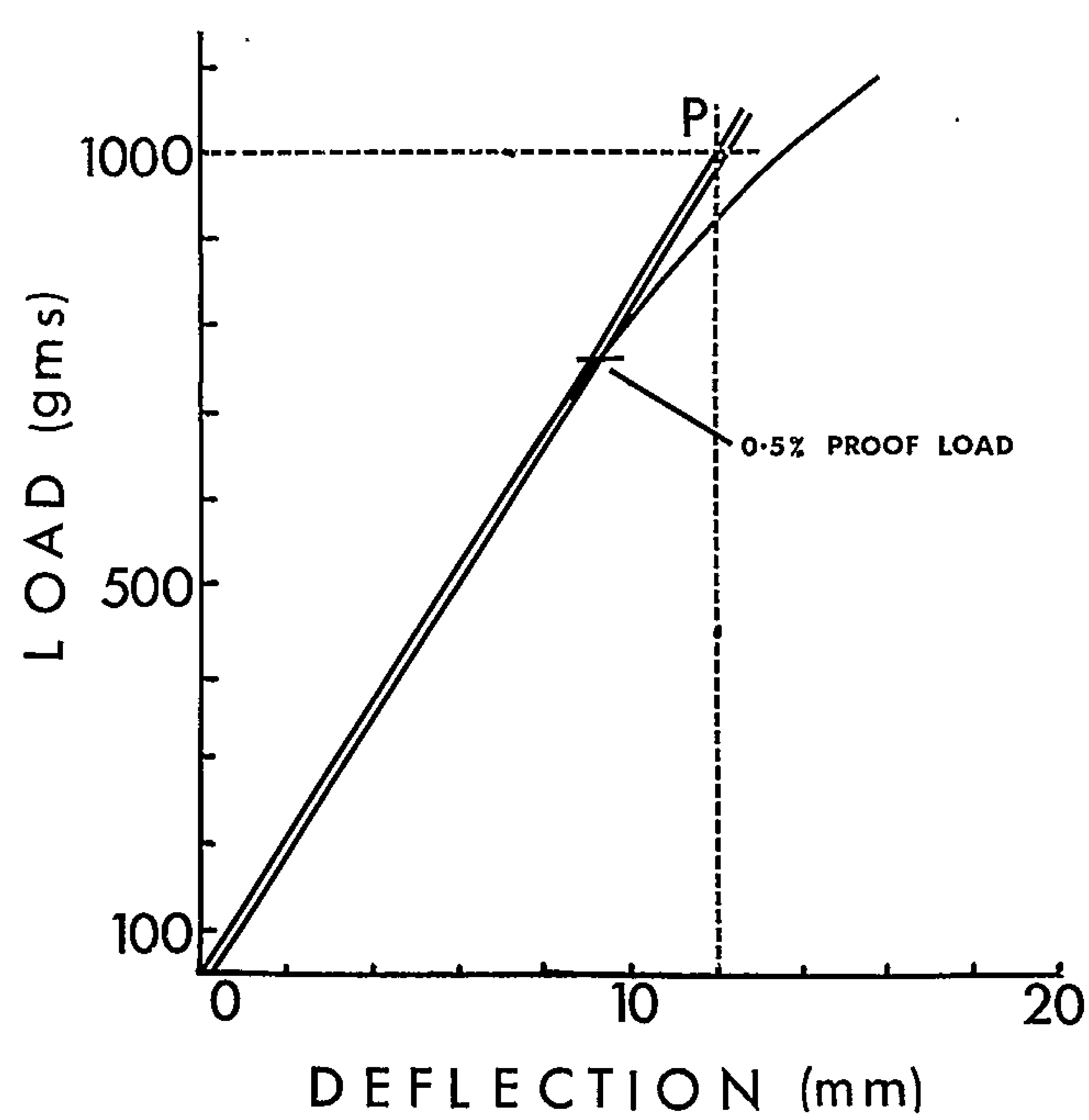


Figure 25.
Determination of 0.5% (Width of Arch) Proof Load of Standard Arches

base of the arch former, the above procedure repeated so that the remaining straight length of arch wire rested along the line E F (Figure 24), the third cylinder was then inserted, procedure repeated so that remaining straight length was parallel to G H. The looped end was then removed from the pin, rotating part placed on cylinder I and this end of the wire made parallel to A B.

With the wire remaining on the arch former scratch marks were made at points I and J and the excess wire at points A and H cut off using a separating disc. The arch was then removed from the arch former (after removal of cylinders II and III and grooves were cut on the inner surfaces of the wire at points I and J, to a depth of approximately 0.2 mm. The rotations were identical for each wire, thus ensuring minimum variation in the shape of the arches, and the inner grooves (which were used to attach the arch to measuring apparatus) were cut at a point taken from a line on the standard arch former.

7.2. HEAT TREATMENT

Ten archwires were made from each type of wire examined and these were heat-treated in a 3 in. diameter tube furnace using a Chromel-Alumel thermocouple indicating temperature to $\pm 2^{\circ}$ C., and controlled to $\pm 5^{\circ}$ C. Time-temperature combinations for heat treatment are given in Table 7. The standard arches were numbered 1 to 10 for each arch of each material.

7.3. APPARATUS

The wires were then subjected to loads in a specifically designed apparatus (Figure 26). The apparatus was tested by loading without specimens to 2,000 gms. - no variation in the suspension part of the apparatus was observed.

7.4. WIDTH OF STANDARD ARCHES

Before any loads were applied to the arch wires the distance between the outer surfaces of the arch wire opposite the grooves I and J were measured using this apparatus and this distance was termed the standard arch width.

7.5. LOAD v DEFLECTION.

Loads were applied in fifty gram increments and a reading of the expansion produced taken. The first reading was taken at 50 gms.

A Cambridge Cathetometer was used to measure the deflection after each load increment and the last reading taken when it became quite obvious that the proof load of the spring had been exceeded.

7.6. DIAMETER OF WIRES

The diameters of the wires used were measured using a screw micrometer by taking five readings around each arch wire.

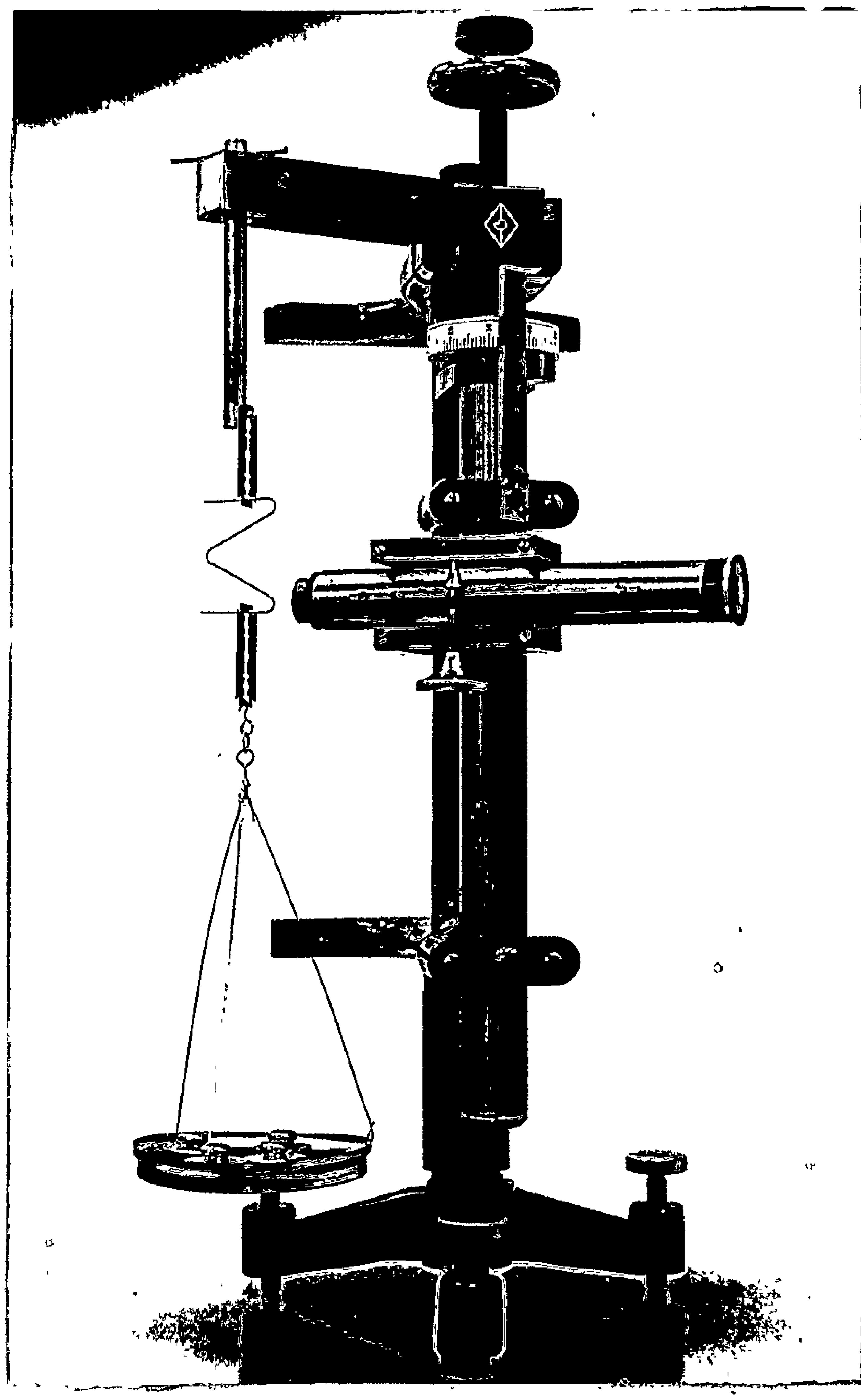


Figure 26.
Apparatus, Load-Deflection Readings.

TABLE 6.

Wires Examined

Material	Nominal Diameter (inches)	Manufacturers Name and Manufacturer
Stainless Steel	0.036	Stainless Steel, Remanit Dentaurum. (20)
Cobalt Chromium Alloy B	0.036	Blue Elgiloy, The Elgin National Watch Company. (59)
Cobalt Chromium Alloy Y	0.036	Yellow Elgiloy, The Elgin National Watch Company. (59)
Nimonic 90	0.036	Nimonic 90, Henry Wiggin and Company Ltd. (28)
Platinised Gold	0.036	Ney Oro Elastic No.12, The J.M. Ney Company. (60)

TABLE 7.

Heat Treatment - Time - Temperature Combinations of Materials Tested

Material	Time (in minutes)	Temperature °C.
Stainless Steel	10	392
Cobalt Chromium Y and B	12	482
Nimonic 90	3	500
Platinised Gold	3	482 then allowed to cool to 232 over 15 minutes

CHAPTER 8.

RESULTS.

The results of the investigation are shown in Tables 8, 9, 10, 11 and Figure 27.

8.1. LOAD v DEFLECTION.

Load v deflection readings are given in the appendix. For each material the mean deflection per fifty gram increment was calculated and the mean load deflection curves of the materials examined are shown in Figure 27. (It is noticed that the steepness of the curves differ).

8.2. DIAMETER OF WIRES

The mean of five readings for each wire are shown in Table 8. The overall mean with standard deviation and coefficient of variation are shown for the different wires used.

The wires used were of a nominal diameter of 0.036 inches (0.9144 mm.) and were found to be uniformly round and of diameters given in Table 8.

8.3. WIDTH OF STANDARD ARCHES.

The width of the standard arches are shown in Table 9. (Width of arch wire has been defined as the width of the arch wire between points I and J, on the outer surfaces of the archwire opposite the grooves at I and J.). Means, standard deviation,

TABLE 8.

Diameter (Millimeters) of Wire Used for Standard Arches
(mean of five readings for each wire)

Number	Material				
	Platinised Gold Wire	Nimonic 90	Stainless Steel Wire	Cobalt Chromium Wire Y	Cobalt Chromium Wire B
1.	0.9144	0.9144	0.8864	0.9067	0.9093
2.	0.0118	0.9169	0.8864	0.9067	0.9093
3.	0.9118	0.9118	0.8864	0.9067	0.9093
4.	0.9118	0.9144	0.8864	0.9067	0.9093
5.	0.9118	0.9144	0.8864	0.9067	0.9118
6.	0.9118	0.9169	0.8864	0.9067	0.9093
7.	0.9118	0.9164	0.8864	0.9067	0.9093
8.	0.9144	0.9169	0.8864	0.9067	0.9093
9.	0.9118	0.9169	0.8864	0.9093	0.9093
10.	0.0118	0.9144	0.8864	0.9093	0.9118
Mean	0.9123	0.9154	0.8864	0.9072	0.9098
Standard Deviation	0.001	0.002	-	0.0001	0.001
Coefficient % of Variation	0.1	0.2	-	0.01	0.1

TABLE 9.

Width of Standard Arch Forms (Millimeters) After Heat Treatment at Various Time Temperature Combinations

Number	Material				
	Platinised Gold Wire	Nimonic 90	Stainless Steel Wire	Cobalt Chromium Wire X	Cobalt Chromium Wire B
1.	43.46	43.61	43.93	45.66	45.22
2.	43.89	43.36	44.34	45.22	44.79
3.	43.27	44.11	44.11	45.43	44.53
4.	43.60	43.87	43.46	45.93	44.76
5.	43.61	42.82	44.00	45.61	45.02
6.	43.52	43.03	43.29	45.53	44.99
7.	43.18	43.94	44.49	45.19	45.91
8.	43.53	44.12	43.77	44.80	44.44
9.	43.81	43.41	43.88	45.53	44.95
10.	43.63	43.35	43.09	45.26	45.76
Mean	43.55	43.56	43.80	45.42	45.04
Standard Deviation	0.22	0.45	0.46	0.31	0.48
Coefficient of Variation %	0.5	1.0	1.0	0.7	1.0
Standard Error	0.07	0.14	0.14	0.09	0.15

TABLE 10.

0.5% (Width of Arch) Proof Load (Gms.) of Standard Arches After Heat Treatment at Various Time-Temperature Combinations

Number	Material				
	Platinised Gold Wire	Nimonic 90	Stainless Steel Wire	Cobalt Chromium Wire Y	Cobalt Chromium Wire B
1.	800	1000	950	820	730
2.	750	970	940	810	680
3.	770	1050	920	850	730
4.	750	1030	950	850	690
5.	780	1010	930	800	760
6.	795	1000	950	800	760
7.	780	1020	950	800	720
8.	800	970	960	810	720
9.	770	1000	970	830	720
10.	810	1030	950	800	730
Mean	780	1008	947	817	724
Standard Deviation	20.9	25.7	14.2	20.0	25.5
Coefficient of Variation %	2.7	2.5	1.5	2.5	3.5
Standard Error	6.6	8.1	4.5	6.2	8.1

TABLE 11.

Spring Rate (Grams per Millimetre) of Standard Arches After Heat Treatment at Various Time-Temperature Combinations

Number	Material				
	Platinised Gold Wire	Nimonic 90	Stainless Steel Wire	Cobalt Chromium Wire Y	Cobalt Chromium Wire B
1.	48.49	88.90	59.88	76.58	79.64
2.	50.95	89.30	60.60	76.26	79.29
3.	50.00	88.48	60.98	77.41	80.00
4.	49.66	88.90	60.98	77.57	78.59
5.	49.08	86.96	59.88	74.37	80.00
6.	49.39	86.58	60.24	77.57	75.93
7.	48.49	90.10	60.98	75.63	88.81
8.	50.00	88.90	59.53	80.72	77.57
9.	50.31	89.30	60.24	77.57	76.91
10.	49.39	89.30	60.98	78.25	77.23
Mean	49.58	88.67	60.43	77.19	79.40
Standard Deviation	0.78	1.09	0.55	1.69	3.59
Coefficient of Variation %	1.6	1.2	0.9	2.2	4.5
Standard Error	0.25	0.35	0.17	0.53	1.14

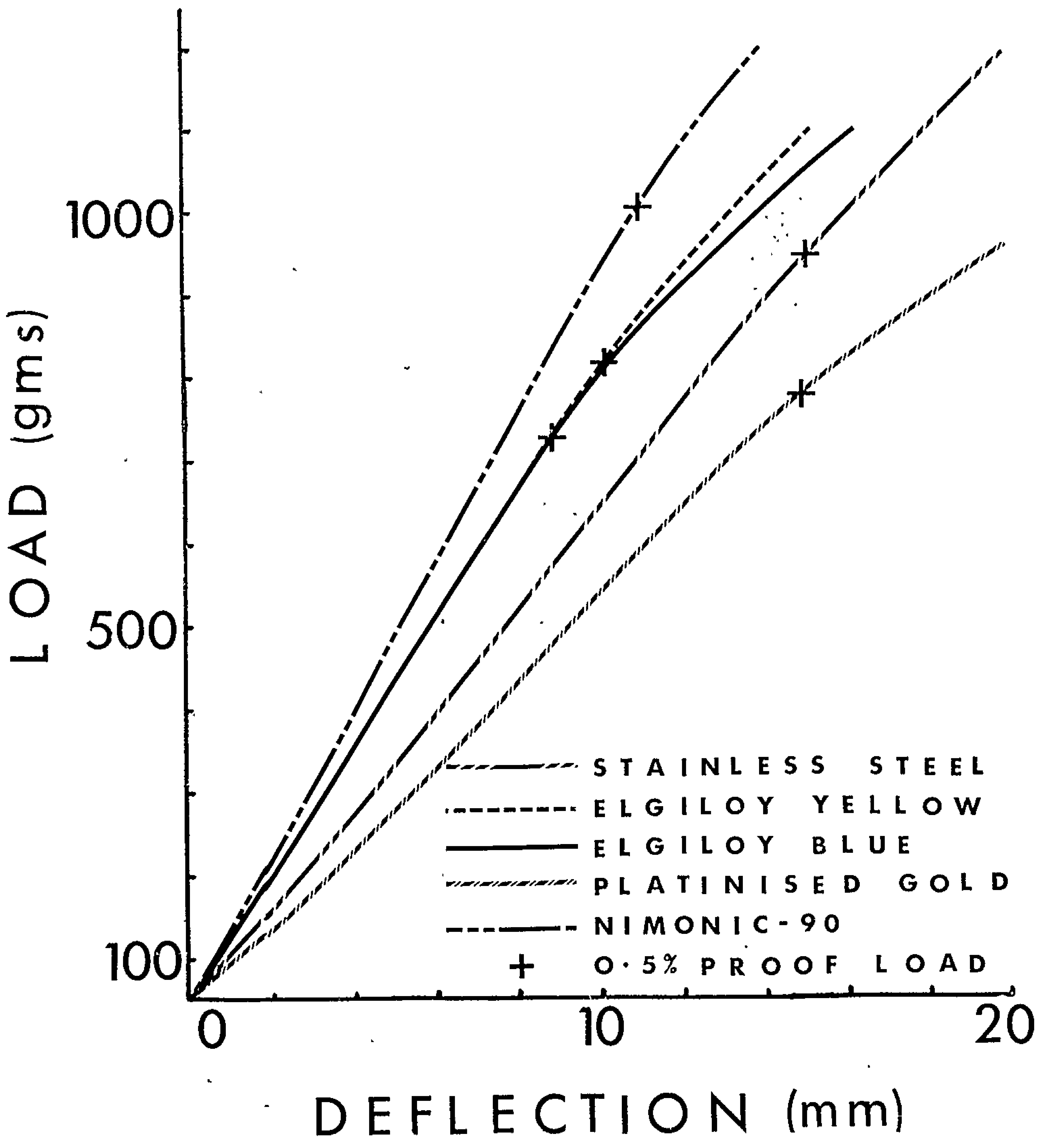


Figure 27.

Load Deflection Curves of Standard Arches after Heat Treatment at Various Time-Temperature Combinations
Note: Initial reading taken with a load of 50 grams.

coefficient of variation and standard error of the mean were calculated for each different wire used.

Mutchler[39] reported that both the cobalt chromium and chromium nickel wires used in his experiments showed some tendency to return to their original form. Provided the form of the arch is otherwise similar, this difference after heat treatment would not alter spring rate and allowance is made for any error in proof load by taking the proof load as the 0.5% (width of arch) proof load.

8.4 PROOF LOAD

The 0.5% (width of arch) proof loads are shown in Table 10. Mean, standard deviation, coefficient of variation and standard error were calculated for each material.

The 0.5% (width of archwire) proof load was determined by plotting the load deflection curve for each arch of each material, e.g. Figure 25. A typical stress-strain curve was obtained and an offset of 0.5% of the initial width of the arch (i.e. 0.22 mm. in example) was drawn parallel to the straight line position of the curve to intersect the curve at point P and this load was then taken as the 0.5% (width of arch) proof load.

The results obtained are significantly different for the materials used. The results are indicative of the proportional limit in bending of the materials studied after heat treatment at various time temperature combination (Table 7).

8.5. SPRING RATE.

The spring rates of the arches for the materials investigated are shown in Table 11.

The spring-rate or load-deflection rate was taken as the ratio of load to deflection for the straight line portion of the load-deflection curve.

This ratio was taken directly from each load deflection curve as in Figure 25, and the results are given in Table 11.

The mean, standard deviation, coefficient of variation and standard error were calculated for each material.

The varying spring rates are indicative of the moduli of elasticity of the alloys examined after heat-treatment at various time-temperature combinations (Table 7). The differences in spring rate of the standard arches of Nimonic 90, platinised gold, stainless steel and the cobalt chromium wires examined are statistically significant as their mean spring rates vary by more than two standard deviations either side of their respective means.

A "t" test was used to determine the significance of the different spring rates of standard arches of cobalt chromium Y and B alloys.

The results of this test are given below and indicate that the difference in spring rate is not statistically significant.

<u>Results of "t" test for difference in spring rate for standard arches of cobalt chromium Y and B after heat treatment at the same temperature time combination.</u>

Difference between means 79.40 - 77.19 = 2.21.

Standard Error of the Difference.

$$(1.14)^2 + (0.95)^2 = 1.48$$

$$\text{"t" ratio} \quad \frac{2.21}{1.48} = 1.5$$

Interpretation using these "t" tables gives a value of P greater than 0.05, indicating that the difference in spring rate is not statistically significant.

CHAPTER 9.

DISCUSSION.

The results from Tables 10 and 11 show that for the wires compared (of nominal diameter 0.036") the platinised gold wire results in the standard arch with the lowest spring rate. Also this material gives a standard arch with a comparatively high proof load.

However, from sections:

2.4 Deflection of Beams.

2.3 Stresses due to Bending

4. General Considerations of Orthodontic Spring Design

it is obvious that relatively small increases or decreases in the cross-section of wires used for orthodontic springs bring about quite large variations in the spring rate and proof load of these springs. Specifically, for springs constructed of round wire the spring rate is proportional to the diameter to the fourth power.

$$\text{Spring rate} \propto d^4 \quad \text{or spring rate} = K_1 d^4 \quad \ldots\ldots \quad (35)$$

and proof load is proportional to the diameter cubed.

$$\text{Proof load} \propto d^3 \quad \text{or proof load} = K_2 d^3 \quad \ldots\ldots \quad (36)$$

where K_1 and K_2 are constants (not the same) depending on the mechanical properties of the material, type of loading, general character and method of support of the spring.

9.1. COMPARISON OF RESULTS

Using equations 35 and 36, the mean results from Tables 10 and 11, the values of K_1 and K_2 were calculated. Assuming that the mechanical properties of the materials used remain the same for small changes in diameter, the values of K_1 and K_2 were calculated and comparison tables were calculated, (Tables 17 and 18), when the diameter of the materials used were changed to give standard arches with (i) The same spring rate.

(ii) The same proof load.

These tables were calculated as follows:-

For each material the values of K_1 and K_2 were calculated (Tables 12 and 13) using the mean results from Tables 10 and 11.

For each measurement in each material the value of K_1 was substituted and the proof load calculated. A Chi-Square test was then made for differences between observed and calculated loads, e.g. Nimonic 90 Table 14.

Similarly differences between observed and calculated proof loads for other alloys investigated were tested using the Chi-Square test. Results are given in Table 15. Similarly for each measurement in each material the value of K_2 was substituted and the theoretical spring rate calculated.

A Chi-Square test was made for differences between calculated and observed spring rates. Results are given in Table 16.

TABLE 12

Calculated Values of K_1 (a constant) for Different Alloys

Alloy	K_1
Platinised Gold Wire	1026
Nimonic 90	1314
Stainless Steel Wire	1360
Cobalt Chromium Wire Y	1094
Cobalt Chromium Wire B	961

TABLE 13

Calculated Values of K_2 (a constant) for Different Alloys

Alloy	K_2
Platinised Gold Wire	71.58
Nimonic 90	126.28
Stainless Steel Wire	97.89
Cobalt Chromium Wire Y	113.96
Cobalt Chromium Wire B	115.89

TABLE 14

Observed and Calculated Proof Loads for Standard Arches of Nimonic 90 Wire After Heat Treatment at 500°C for 3 minutes

Number	Proof Load (Gms)		
	Observed O	Calculated T	$\frac{(O-T)^2}{T}$
1.	1000	1005	0.0248
2.	970	1013	1.9061
3.	1050	996	2.7771
4.	1030	1005	0.6067
5.	1010	1005	0.0247
6.	1000	1013	1.0169
7.	1020	1013	0.0480
8.	1000	1013	0.1690
10.	1030	1005	0.6067
			x^2 8.086

TABLE 15

Differences Between Observed and Calculated Proof Loads of Different Alloys after Heat Treatment at Various Time Temperature Combinations

Alloy	x^2
Platinised Gold Wire	4.88
Nimonic 90	8.09
Stainless Steel Wire	1.91
Cobalt Chromium Wire Y	4.33
Cobalt Chromium Wire B	7.47

TABLE 16

Differences Between Observed and Theoretical Spring Rates of Standard Arches After Heat Treatment at Various Time Temperature Combinations

Alloy	x^2
Platinised Gold Wire	.531
Nimonic 90	.013
Stainless Steel Wire	.045
Cobalt Chromium Wire Y	.335
Cobalt Chromium Wire B	.314

From x^2 table, the value of x^2 at P = .90 for nine degrees of freedom is 4.168 indicating that the differences between observed and calculated spring rates are not significant and that the mean results from Table 11 can be used for further calculations. From X^2 table of value of x^2 at P = 0.5 for nine degrees of freedom is 8.343 indicating that the differences between observed and calculated proof loads are not considered to be statistically significant and that mean results from Table 10 can be used for further calculations.

Using values of K_1 and K_2 (which were shown to be satisfactory by the Chi-Square test), and assuming that all factors (e.g. modulus of elasticity, proportional limit in bending, arch form) except diameter of wire used to form arches, remained constant, the theoretical diameters of similar standard arches of the alloys used were calculated to give standard arches of

(a) the same spring rates

(b) the same proof load

the results are given in Table 17 and 18.

From Table 17 it can be seen that if the diameters of the wires used to form the standard arches are changed the stainless steel and platinised gold arches will have the lowest spring rates and the arch with the highest spring rate is of cobalt chromium B. (Assuming no changes in mechanical properties of wires with variation in diameter.)

TABLE 17

Comparison of Standard Arches of Different Alloys with the Same Spring Rate after Heat Treatment at Various Time Temperature Combinations

	Material				
	Platinised Gold	Nimonic 90	Stainless Steel	Cobalt Chromium Y	Cobalt Chromium B
Spring Rate grams/mm.	49.58	49.58	49.58	49.58	49.58
Diameter of Wire (mm.)	0.9123	0.7915	0.8435	0.8120	0.8087
Proof Load grams	780	651	816	586	508

TABLE 18

Comparison of Standard Arches of Different Alloys with the Same Proof Load

After Heat Treatment at Various Time Temperature Combinations

	Material				
	Platinised Gold	Nimonic 90	Stainless Steel	Cobalt Chromium Y	Cobalt Chromium B
Proof Load (grams)	780	780	780	780	780
Diameter of Wire (mm)	0.9123	0.8404	0.8308	0.8933	0.9327
Spring Rate Grams (mm)	49.58	62.96	46.62	72.58	87.68

9.2 CLINICAL SIGNIFICANCE OF RESULTS

In terms of efficiency of the appliance, the most suitable materials (of those compared) are the platinised gold and stainless steel. i.e. they have the greatest ranges of action for a given proof load. The least suitable material is the Blue Elgiloy.

Stainless steel wire has several disadvantages when used for expansion arches. These are:-

(1) Stainless Steel Wire is supplied in the hard drawn condition and these is some difficulty in constructing the appliance.

(2) Heat treatment is critical and must be carried out in a controlled furnace or dental oven. Heating over 400°C decreases the corrosion resistance (Ingerslev)[30] and annealing of the wire starts at 600 - 650°C and since clinically satisfactory low fusing solder melts in the range 650 - 750°C some softening of the wire must be expected if the wire is soldered (Wilkinson)[67].

Platinised gold wire has a spring rate (after heat treatment) comparable to that of heat treated stainless steel for equivalent proof loads (wire must be of larger diameter), and has the advantage that the wire is supplied in an annealed condition (making fabrication of appliances easy) and the appliance can be heat treated after gold soldering. The

The disadvantage of platinised gold wire for this type of appliance is that for the wire to obtain its maximum mechanical properties it must be heat-treated in a controlled furnace or dental oven; i.e. experimental wire 900°F and allowed to cool from that temperature to 450°F in fifteen minutes.

The cobalt chromium wires B and Y give high spring rates for standard arches for equivalent proof loads. Standard arch of cobalt chromium B has a spring rate almost double that of a standard arch of heat treated stainless steel or platinised gold. Mutchler(39) observed that this material can be heated at 650° for a period of up to three minutes without seriously affecting its mechanical properties. Brockhurst(7), (Figure 21) shows that the proportional limit of cobalt chromium Y decreases when heated above 600°C. These results indicate that while this material can be soldered clinically, care must be taken not to overheat, or to heat for too long a period otherwise some softening of the wire will result.

The Nimonic 90 wire gives a standard arch with spring rate, 20-25% greater than stainless steel or platinised gold for the equivalent proof load.

However this alloy has two distinct advantages:

(a) As supplied it is relatively ductile.

(b) It can be heated over a wide range of temperatures (300° - 800° (within the orthodontic soldering range) without seriously affecting its mechanical properties. Heating within this range also produces hardening of the wire.

These two factors make this alloy very acceptable clinically and although not quite as good as stainless steel where high proof loads are required, this would be the most suitable of the materials studied for upper lingual expansion arches.

CHAPTER 10.

SUMMARY AND CONCLUSIONS

(1) The relevant spring properties (proof load and spring rate), of a nickel base alloy wire, Nimonic 90, are compared with those of (i) a stainless steel alloy

(ii) a platinised gold alloy

(iii) a cobalt chromium alloy

when bent in a structural form similar to the upper lingual expansion arch.

(2) Of the materials compared the stainless steel and the platinised gold alloy wires have the better spring properties after heat treatment.

(3) The cobalt chromium wire studied has the least desirable spring properties of the materials compared after heat treatment.

(4) The spring properties of the nickel base alloy wire studied are not as good as those of the platinised gold (20% less) or stainless steel alloy (25% less) wires used for comparative purposes but are significantly better than those of the cobalt chromium alloys (10% better than Y, 22% better than B) studied, after heat treatment.

(5) The nickel base alloy examined (Nimonic 90) which was initially selected from a number of high strength chromium-

protected alloy wires for partial denture clasp construction by gold soldering (Brockhurst)[7], should, by virtue of its

(i) relatively good spring properties (due to a high proportional limit after heat treatment)

(ii) high ductility before heat treatment

(iii) wide range and high temperatures for heat treatment,

should be a suitable material for use in upper lingual expansion appliances.

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A P P E N D I X

Load Deflection Readings, Platinised Gold Standard Archwires after Heat Treatment at 482°C for 3 Minutes, Then Allowed to cool to 232°C over 15 minutes

Load Gms.	1		2		3		4		5		6		7		8		9		10		Mean	
	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø
50																						
100	122	122	111	111	116	116	115	115	118	118	117	117	118	118	110	110	112	112	116	116	115	115
50	112	234	108	219	111	227	110	225	114	232	111	228	112	230	111	221	111	223	113	229	112	227
200	111	345	105	324	107	334	108	333	110	342	109	337	110	340	108	329	106	329	108	337	108	335
50	105	450	102	426	105	439	102	435	107	449	105	442	107	447	105	434	103	432	107	444	105	440
300	106	556	101	527	102	541	100	535	103	552	102	544	103	550	101	535	102	534	104	548	102	542
50	100	656	96	623	99	640	98	633	101	653	100	644	102	652	99	634	98	632	101	649	100	642
400	100	756	94	717	97	737	94	727	100	753	98	742	98	750	99	733	97	729	98	747	98	740
50	98	854	94	811	97	834	93	820	97	850	97	839	99	849	96	829	96	825	99	846	96	836
500	96	950	92	903	94	928	94	914	97	947	95	934	98	947	95	924	94	919	98	944	95	931
50	99	1049	93	996	95	1023	93	1007	96	1043	96	1030	99	1045	96	1018	95	1014	97	1041	96	1027
600	97	1146	93	1089	96	1119	94	1101	98	1141	96	1126	100	1145	97	1115	95	1109	99	1140	96	1123
50	100	1246	96	1185	97	1216	97	1198	99	1240	101	1227	102	1248	98	1213	101	1210	100	1240	99	1222
700	103	1349	99	1284	104	1320	100	1298	106	1346	103	1330	106	1354	103	1316	100	1310	103	1343	103	1325
50	111	1460	105	1389	109	1429	105	1403	110	1456	109	1439	115	1469	109	1425	105	1415	113	1456	109	1434
800	120	1580	113	1502	119	1548	113	1516	125	1581	120	1559	122	1591	120	1545	115	1530	121	1577	119	1553
50	123	1703	124	1626	128	1676	124	1640	129	1710	139	1698	131	1722	140	1685	124	1654	135	1712	130	1683
900	143	1846	136	1762	145	1821	134	1774	149	1859	145	1843	149	1871	134	1819	143	1797	143	1855	142	1825
50	159	2005	163	1925	158	1979	135	1909	154	2013	152	1995	171	2042	166	1985	163	1960	168	2023	159	1984
1000	172	2177	178	2103	182	2161	170	2079	190	2203	182	2177	176	2218	181	2166	169	2129	199	2222	179	2163
50	184	2361	209	2312	199	2360	176	2255	223	2426	206	2383	208	2426	219	2385	204	2333	207	2429	204	2367

* Deflection /50 gms.
ø Total Deflection.

Load Deflection Readings, Stainless Steel Standard Archwires

after Heat Treatment at 392°C for 10 minutes

Load Gms.	1		2		3		4		5		6		7		8		9		10		Mean	
	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ
50																						
100	93	93	87	87	92	92	93	93	92	92	91	91	87	87	92	92	93	93	93	93	91	91
50	90	183	87	174	87	179	89	182	88	180	91	182	88	175	92	184	91	184	90	183	89	181
200	86	269	87	261	87	266	88	270	87	267	86	268	86	261	91	275	90	274	88	271	88	268
50	87	356	85	346	86	352	87	357	85	352	87	355	84	345	88	363	88	362	86	357	86	355
300	80	436	82	428	83	435	84	441	87	439	85	440	84	429	85	448	83	445	85	442	84	438
50	89	525	82	510	82	517	83	524	83	522	83	523	81	510	86	534	86	531	84	526	84	522
400	83	608	82	592	81	598	82	606	83	605	82	605	81	591	83	617	83	514	82	608	82	604
50	82	690	81	673	82	680	80	686	82	687	82	687	81	672	83	700	83	697	83	691	82	686
500	82	772	81	754	81	761	80	766	81	768	81	768	80	752	83	783	82	779	81	772	81	767
50	81	853	81	835	81	842	79	845	82	850	80	848	81	833	81	864	80	859	80	852	81	848
600	81	934	81	916	79	921	79	924	82	932	81	929	79	912	81	945	81	940	80	932	80	928
50	82	1016	82	998	81	1002	78	1002	82	1014	80	1009	81	993	82	1027	79	1019	80	1012	81	1009
700	82	1098	81	1079	80	1082	78	1080	84	1098	82	1091	81	1074	82	1109	80	1099	80	1092	81	1090
50	84	1182	84	1163	83	1165	81	1161	84	1182	82	1173	82	1156	84	1193	80	1179	82	1174	82	1173
800	84	1266	85	1248	85	1250	79	1249	88	1270	86	1259	84	1240	83	1276	80	1259	82	1256	84	1257
50	87	1353	88	1336	85	1335	82	1331	84	1354	84	1343	86	1326	86	1362	81	1340	83	1339	85	1342
900	89	1442	88	1424	87	1422	82	1413	94	1448	88	1431	88	1414	89	1451	83	1423	83	1424	87	1429
50	94	1536	93	1517	92	1514	86	1499	93	1541	91	1522	91	1505	92	1543	85	1508	85	1511	90	1520
1000	95	1631	95	1612	93	1607	88	1587	95	1636	91	1613	92	1597	96	1639	85	1593	87	1604	92	1612
50	98	1729	97	1709	98	1705	92	1679	97	1733	97	1710	97	1694	97	1736	89	1682	93	1698	95	1707
1100	100	1829	101	1810	98	1803	96	1775	102	1835	101	1811	98	1792	103	1839	91	1773	102	1800	99	1807
50	105	1934	106	1916	100	1903	101	1876	106	1941	104	1915	102	1894	104	1943	95	1868	104	1904	103	1909
1200	112	2046	111	2027	114	2017	107	1983	109	2050	110	2025	109	2003	110	2053	105	1973	111	2015	110	2015

* Deflection /50 gms.

ϕ Total Deflection.

Load Deflection Readings, Nimonic 90 Standard Archwires

After Heat Treatment at 500°C for 3 minutes

Load Gms.	1		2		3		4		5		6		7		8		9		10		Mean	
	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø	*	ø
50																						
100	60	60	60	60	62	62	63	63	63	63	61	67	59	59	61	61	62	62	61	61	61	61
50	58	118	58	118	60	122	60	123	61	124	59	120	58	117	58	119	59	121	59	120	59	120
200	58	176	57	175	59	181	58	181	60	184	59	179	58	173	51	176	59	180	58	178	58	178
50	56	232	57	232	58	239	57	238	60	244	59	238	57	232	57	233	56	236	56	234	58	236
300	56	288	56	288	57	296	57	295	57	301	58	296	55	287	56	289	56	292	56	290	56	292
50	55	343	54	342	57	353	56	351	57	358	57	353	54	341	56	345	55	347	55	345	56	348
400	55	398	54	396	56	409	55	406	57	415	56	409	56	397	55	400	54	401	54	399	55	403
50	54	452	54	450	55	464	54	460	54	469	57	466	53	450	54	454	54	455	54	453	54	457
500	53	505	54	504	54	518	53	513	55	524	56	522	55	505	55	509	54	509	54	507	55	512
50	54	559	54	558	54	572	54	567	55	579	55	577	53	558	54	563	53	562	53	560	53	565
600	55	614	54	612	54	626	54	621	55	634	55	632	54	612	56	619	54	616	53	613	55	620
50	55	669	55	667	54	680	54	675	55	689	56	688	54	666	55	674	54	670	54	667	54	674
700	56	725	55	722	54	734	56	731	56	745	57	745	54	720	56	730	55	725	55	722	56	730
50	57	782	57	779	55	789	56	787	57	802	58	803	56	776	57	787	56	781	56	778	55	785
800	58	840	60	839	56	845	57	844	58	860	59	862	57	833	58	845	57	838	57	835	59	844
50	60	900	59	898	57	902	58	902	59	919	61	923	57	890	60	905	60	898	60	895	59	903
900	64	964	66	964	60	962	59	961	64	983	65	988	59	949	64	969	61	959	60	955	62	965
50	64	1028	66	1030	62	1024	63	1024	64	1047	64	1052	64	1013	65	1034	62	1021	64	1019	65	1030
1000	69	1097	70	1100	64	1088	66	1090	69	1116	71	1123	64	1077	68	1102	67	1088	67	1086	67	1097
50	73	1170	70	1170	69	1157	69	1159	73	1189	73	1196	68	1145	71	1173	69	1157	69	1155	70	1167
1100	75	1245	78	1248	70	1227	72	1231	77	1266	74	1270	72	1217	75	1258	72	1229	74	1229	75	1242
50	81	1326	76	1324	77	1304	76	1307	84	1350	86	1356	78	1295	81	1339	78	1307	78	1307	78	1321
1200	90	1416	90	1410	83	1387	79	1386	90	1440	87	1443	79	1374	90	1429	80	1387	83	1390	85	1406

* Deflection /50 gms.
ø Total Deflection.

B

Load Deflection Readings, Cobalt Chromium/Standard Archwires

After Heat Treatment at 482°C for 12 Minutes

Load	1		2		3		4		5		6		7		8		9		10		Mean	
Gms.	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ
50																						
100	68	68	73	73	70	70	67	67	68	68	70	70	64	64	69	69	67	67	70	70	69	69
150	68	136	68	141	68	138	67	134	66	134	71	141	64	128	69	138	66	133	66	136	67	136
200	64	200	66	207	65	203	65	199	64	198	69	210	60	188	66	204	66	199	66	202	65	201
50	63	263	65	272	65	268	64	263	63	261	67	277	61	249	65	269	62	261	64	266	64	265
300	62	325	63	335	66	334	64	327	63	324	65	342	59	308	65	334	62	323	64	330	63	328
50	63	388	63	398	65	399	63	390	63	387	65	407	62	370	63	397	62	385	63	393	63	391
400	62	450	62	460	63	452	63	453	63	450	65	472	60	430	63	460	62	447	63	456	62	453
50	62	512	63	523	63	515	63	516	61	511	65	537	61	491	64	524	62	509	63	519	63	516
500	62	574	62	585	63	578	65	581	62	573	65	602	63	554	64	588	62	571	64	583	63	579
50	64	638	65	650	63	641	67	648	62	635	65	667	63	617	66	654	65	636	66	649	65	644
600	65	703	67	717	66	707	67	715	66	701	69	736	64	681	68	722	67	703	68	717	66	710
50	69	772	71	788	67	774	70	785	66	767	70	806	69	750	70	792	67	770	73	790	69	779
700	69	841	74	862	69	843	76	861	70	837	74	880	69	819	73	865	73	843	76	866	73	852
50	76	917	78	940	75	918	78	939	72	909	76	956	74	893	80	945	82	925	78	944	77	929
800	82	999	83	1023	85	1003	87	1026	78	981	79	1035	78	971	82	1027	85	1010	88	1032	82	1011
50	78	1077	86	1109	80	1083	93	1119	83	1070	85	1120	81	1052	94	1121	92	1102	90	1122	87	1098
900	85	1162	100	1209	92	1175	94	1213	86	1156	93	1213	87	1139	101	1222	95	1197	98	1220	93	1191
50	97	1259	101	1310	94	1269	104	1317	103	1259	102	1315	98	1237	108	1330	97	1294	105	1325	101	1292
1000	110	1369	112	1422	107	1376	115	1432	106	1365	95	1410	95	1332	120	1450	105	1399	114	1439	107	1399
50	117	1486	121	1543	119	1495	120	1552	110	1475	103	1513	108	1440	133	1583	117	1516	127	1566	118	1517
1100	134	1620	131	1674	135	1630	129	1681	118	1593	122	1635	115	1555	126	1709	128	1644	132	1698	127	1644

* Deflection /50 gms.

ϕ Total Deflection.

Load Deflection Readings, Cobalt Chromium Y Standard Archwires

after Heat Treatment at 482°C for 12 minutes

Load Gms.	1		2		3		4		5		6		7		8		9		10		Mean	
	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ	*	ϕ
50																						
100	67	67	71	71	72	72	68	68	74	74	66	66	70	70	70	70	68	68	68	68	69	69
50	67	134	70	141	66	138	67	135	70	144	66	132	67	137	66	136	65	133	66	134	65	136
200	66	200	68	209	66	204	63	198	69	213	65	197	66	203	66	202	65	198	64	198	66	202
50	65	265	66	275	65	269	63	261	69	282	64	261	66	269	64	266	63	261	63	261	65	267
300	64	329	66	341	63	332	63	324	69	349	62	323	65	334	64	330	64	325	63	324	64	331
50	63	392	64	405	63	395	62	386	67	415	63	386	64	398	63	393	62	387	63	387	63	394
400	63	455	63	468	63	458	62	448	66	480	62	448	63	461	62	455	61	448	62	449	63	457
50	63	518	63	531	62	520	62	510	65	546	62	510	64	525	63	518	61	509	63	512	63	520
500	63	581	63	594	62	582	61	571	66	612	65	575	63	588	63	581	63	572	63	575	63	583
50	64	645	63	657	64	646	63	634	68	670	64	639	66	654	64	645	63	635	63	638	63	646
600	66	711	64	721	66	712	66	700	67	737	67	706	68	722	67	712	64	699	64	702	66	712
50	66	777	68	789	68	777	66	766	71	808	67	773	68	790	68	780	66	765	67	769	68	780
700	69	846	68	857	69	846	69	835	72	880	69	842	72	862	69	849	69	834	68	837	69	849
50	70	916	71	928	69	915	73	908	79	959	72	914	73	935	71	920	70	904	71	908	72	921
800	76	1002	75	1003	71	986	74	982	78	1037	77	991	76	1011	77	997	74	978	73	981	76	997
50	77	1079	77	1080	76	1062	76	1058	79	1116	79	1070	80	1091	75	1072	75	1053	75	1056	77	1074
900	77	1156	79	1159	75	1137	80	1138	87	1203	83	1153	81	1172	83	1155	77	1130	81	1137	80	1154
50	83	1239	83	1242	80	1217	85	1223	97	1310	84	1237	87	1259	86	1241	88	1218	82	1219	86	1240
1000	88	1317	90	1332	82	1299	88	1311	97	1407	93	1330	93	1352	86	1327	85	1303	85	1304	88	1328
50	96	1413	100	1432	83	1382	96	1407	100	1507	97	1427	99	1451	95	1422	93	1396	88	1392	95	1423
1100	101	1514	101	1533	96	1478	99	1506	113	1620	98	1525	100	1551	97	1519	104	1500	103	1495	100	1523

* Deflection /50 gms.

ϕ Total Deflection.