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The tensile strength of hardmetals

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In conventional bend tests on hardmetal specimens with a rectangular cross-section the strength values exhibit a wide scatter as a result of fracture being initiated from pores and inclusions. A new bend test-piece geometry has been devised which subjects a relatively small volume of material to a high tensile stress and so reduces the probability of fracture starting from defects. The test gives reproducible results with low scatter, and, by suppressing defect initiated failures, it enables a more accurate assessment to be made of the effect of metallurgical variables, such as grain-size and composition, on strength.

1. Introduction

Hardmetal components are generally designed so that they are subjected to predominantly compressive stresses in service. However, tensile stresses cannot be eliminated completely, and tensile properties are considered to be important because hardmetals possess a low ductility in tension. Conventional uniaxial tensile tests have not been widely used for hardmetals because of the inherent difficulties with materials of low ductility but bend tests are frequently used to measure tensile strength [1]. The standard procedure for determining the bend strength of hardmetals involves calculating the maximum tensile stress at the surface of the specimen from a formula based on elasticity theory, although the elastic limit can often be exceeded. This calculation has recently been shown to give misleading values for the strength of hardmetals because failure of the bend specimen does not always begin at the position of maximum stress at the surface, and in a proportion of specimens fracture is caused by the presence of defects, such as pores and inclusions, situated beneath the surface. In addition, it has been shown [2] that there is a Griffith-type relation between the nominal stress at the position of fracture initiation and the size of the defect that causes fracture and that the use of this relation enables the scatter in the results of the bend test to be rationalized. However, it was also found [2] that in a small number of specimens where fracture started from small pores or coarse carbide grains the bend strength was independent of the size of the fracture source and reached a limiting value.

Knowledge of the limiting strength could be useful to hardmetal users and manufacturers since its value is determined by metallurgical factors rather than by defect content. Consequently, a new test-piece shape has been developed to measure this strength. The new shape is produced by chamfering the central portion of a bend test specimen, as shown in Fig. 1, so that the volume of material subject to a high tensile stress is reduced to several cubic millimetres or less [3]. This procedure effectively reduces the likelihood of defect-initiated failures and ensures that a value of the limiting or tensile strength can be determined from a relatively small number of tests.

In order to examine the practicability of using the new test-piece shape for measuring limiting strength values a series of measurements were made on bend specimens, with conventional shapes and with chamfered central regions, prepared from a variety of hardmetals. The effect of surface preparation of the chamfered specimens was also investigated.

2. Materials

The work was performed on six tungsten carbide hardmetals. Details of the properties as supplied by Wickman Wimet Ltd are given in Table I where the hardmetals are referred to as 6F, 9F, 11F, 6C, 9C and 11C according to their cobalt content in

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TABLE I Physical properties of hardmetals

Material	Co (wt %)	Carbide grain size (μm)	Specific gravity	Hardness (HV_{30})	Coercivity (kA m^{-1})	Total carbon content (wt %)	Porosity ASTM B406/64
6F	6	1.44	15.01	1535–1560	14.3–15.1	5.82	A1
9F	9	1.40	14.64	1385–1420	11.9–12.5	5.59	A1
11F	11	1.41	14.45	1305–1355	10.1–11.1	5.49	A1
6C	6	4.81	15.08	1225–1245	5.9– 6.1	5.78	<B1
9C	9	4.70	14.71	1120–1140	5.2– 5.3	5.61	<A1
11C	11	5.12	14.44	1090–1115	4.1– 4.5	5.48	<A1

wt % and carbide grain-size: fine (F) and coarse (C). Several specimens of 6F and 11F were tested after a hot isostatic pressing, HIP, treatment.

3. Testing details

Three and four-point bend tests were performed on plain rectangular specimens. The 3-point bend specimens were 19 mm long by 6.3 mm wide by 4.9 mm high and conformed with the current standard [1] for transverse rupture testing of hardmetals; the span of the bend rig was approximately 14 mm. The four-point bend specimens were 40 mm long by 2.5 mm wide by 4.9 mm high, and the major and minor spans of the test rig were 29.4 and 9.8 mm respectively. The as-received specimens were wet ground parallel to the length with a resin-bonded diamond wheel to remove about 0.2 mm from the as-sintered surfaces. The diamond wheel had a grit size of 150, the peripheral speed of the wheel was approximately 30 m sec^{-1}, and no pass exceeded 0.01 mm. The last 0.05 mm was diamond lapped to remove surface residual stresses introduced by grinding. The opposite lapped faces were parallel within 0.001 mm, and the height and width of the test-pieces were measured at the midpoint of the length to an accuracy of ± 0.01 mm. The edges of the specimens were chamfered along the tension side in accordance with the previously mentioned standard.

The modified bend test-pieces (Fig. 1) were prepared by grinding the central portion of the specimens to form the shape of an inverted V. The included angle at the apex of the V was 90° and the radius of the apex was about 0.02 mm. The chamfered specimens were 40 mm long, 4.9 mm high and about 1.25 mm wide and were tested in a three-point bend rig with a span of 29.4 mm. The specimens were shaped initially by diamond grinding, and in order to study the effect of the type of surface preparation of the chamfered region a variety of further treatments was used on some of the specimens. Thus, tests were performed on specimens that were as-ground (both longitudinal and transverse), or ground and lapped, or ground and heat-treated. The heat treatment consisted of one hour at either 400° C or 800° C in a vacuum followed by furnace cooling. Some difficulty was experienced in devising a simple method of lapping the chamfered specimens. Consequently the effect of a lapping treatment was investigated on chamfered specimens in which the height of the rectangular cross-section at either end of the specimen was reduced by grinding to a new height $W(1-p)$, where W and p are as shown in Fig. 1. About 0.05 mm was removed from the chamfered region during the diamond lapping treatment.

All the tests were performed at room temperature, 20° C, and the load was applied at a constant rate not exceeding 300 N sec^{-1}. The fracture origins of the broken specimens were identified by examination of the fracture faces both by optical and scanning electron microscopy.

In order to confirm that the formula, given in the appendix, for the stress at the apex of the modified specimens was correct, a scale model of the fully chamfered specimens was prepared from

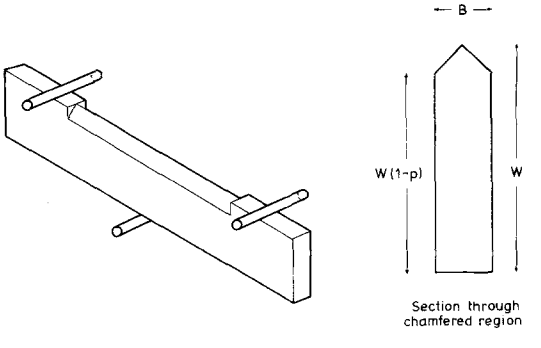

Figure 1 Schematic diagram of chamfered bend-test specimen

quenched and tempered EN24 steel and strain-gauged at various positions along the chamfered portion. The model, which was about seven times larger than the hardmetal specimens, was tested in a large 3-point bend rig of 250 mm total span. Care was taken to ensure that the elastic limit was not exceeded during loading, and the strains were recorded at several values of applied bending moment during loading and unloading.

4. Stress formulae

The maximum limiting stress, σ_L, in the normal bend specimen was calculated from

$$\sigma_L = \frac{3PL}{BW^2} \quad (1)$$

where P is the load at failure, B and W are the specimen width and height respectively, L is the distance between the inner and outer loading points in the 4-point bend rig and $2L$ is the span of the 3-point bend rig.

The maximum stress at the apex of the fully chamfered specimen can be calculated from

$$\sigma_T = \frac{MC}{I} \quad (2)$$

where M is the bending moment, I is the moment of inertia of the chamfered cross-section and C is the distance from the apex to the neutral axis of that part of the bend test specimen possessing the chamfer.

A general expression for the section modulus, I/C, can be derived if a parameter p is used to describe the shape of the wedge (Fig. 1). W_p is the height of the wedge-shaped region, and $W(1-p)$ is the height of the parallel section of the specimen below the wedge. Thus it is found that (see Appendix):

$$\frac{I}{C} = \tfrac{1}{6}BW^2 \frac{1-2p+2p^2-p^3+p^4/6}{1-p^2/3} \quad (3)$$

hence

$$\sigma_T = \frac{6M}{BW^2} \frac{1-p^2/3}{1-2p+2p^2-p^3+p^4/6}$$

$$\sigma_T = \frac{3PL}{BW^2} \frac{1-p^2/3}{1-2p+2p^2-p^3+p^4/6} \quad (4)$$

5. Results and discussion

5.1. Strain-gauged model

The strains measured on the strain-gauged model and the strains calculated using Equation 4 agree to within 6 to 8% and indicate that the position of maximum stress on the tensile surface beneath the central roller is spread over a region corresponding in length to about 5% of the total span. To calculate the stresses it was assumed that the value of Young's modulus for the steel was 210 kN mm^{-2}, but the true value may have been up to 5% higher and this may account for the small discrepancy between the measured and calculated stresses.

5.2. Conventional specimens

Table II summarizes the results obtained in conventional bend tests. The tests on the standard fine-grained materials indicated that a large number of specimens were needed to provide a value for the limiting strength. The number could be reduced by using an HIP treatment to close up large defects, such as pores, that caused premature failure. Nevertheless, as shown in Table II, some specimens failed to reach the limiting strength, and observation of the fracture faces showed that these specimens had failed from defects that contained inclusions which had not been removed by the HIP treatment. The limiting strength values for the coarse-grained materials were easier to obtain from the standard tests because they were probably tougher and thus inherently more tolerant of defects. Even so, about 75% of the specimens tested failed to reach the limiting strength. The limiting strength value obtained in the 3-point test was different from that measured in the 4-point test because the small span to height ratio, about 3 to 1, of the 3-point bend test specimens produced a wedging action as a result of which the calculated stress was 10 to 15% greater than the true stress. Values of limiting strength corrected for the wedging effect are shown in Table II.

Thus the limiting strength could be obtained from conventional bend tests, but unless they were HIP treated a large number of specimens were required and, particularly for the fine-grained materials, it was not always certain that a limiting strength value could be measured.

5.3. Chamfered specimens

The results of tests on chamfered specimens are shown in Tables III and IV. The strength values were calculated from Equation 4. It can be seen that the chamfered specimen was much more effective than the standard specimen in providing

TABLE II Conventional bend test results

Specimen	Surface* preparation	Number of specimens tested	Number of specimens that gave a σ_L value	Limiting strength, σ_L (kN mm^{-2})		
				4-pt	3-pt nominal	3-pt corrected for short span effect [4]
6F	G_L, L	11	0	–	–	–
6F	G_L, L	8	6	–	2.9	2.5
11F	G_L, L	23	1	–	3.0	2.6
11F IHP	G_L, L	10	8	–	3.0	2.6
6C	G_L, L	22	5	2.1–2.2	2.5–2.6	2.2
9C	G_L, L	20	5	2.2–2.4	2.6–2.7	2.3
11C	G_L, L	14	5	2.2–2.3	2.6–2.7	2.3

*G_L: ground longitudinally; L: diamond lapped.

TABLE III Chamfered 3-point bend test results on 6C

Specimen	Surface* preparation	Number of specimens tested	Number of specimens tested that gave a σ_L value	Limiting strength (kN mm^{-2})
6C a	G_L	4	4	2.65
6C b	G_L, HT (400)	2	2	2.65
6C c	G_L, HT (800)	4	4	2.20
6C d	G_T	3	3	2.50
6C e	G_T, HT (800)	3	2	2.25
†6C f	G_L	3	3	2.65
†6C g	G_L, L	4	4	2.60
†6C h	G_L, HT (800)	2	2	2.60

*G_L, ground longitudinally; G_T, ground transversely; HT (400), heat treated at 400° C for 1 h in a vacuum; HT (800), heat treated at 800° C for 1 h in a vacuum; L, diamond lapped.
†6C, g and h, specimens with reduced end sections.

TABLE IV Chamfered 3-point bend tests on 6F, 9F, 11F, 9C and 11C

Specimen	Surface* preparation	Number of specimens tested	Number of specimens tested that gave a σ_L value	Limiting strength (kN mm^{-2})
6F	G_T	3	0	–
6F	G_T, HT (800)	3	3	2.45
9F	G_T	3	2	3.30
	G_T, HT (800)	3	1	2.45
11F	G_T	3	3	3.30
	G_T, HT (800)	3	3	2.65
	G_L	1	1	2.95
9C	G_T	3	3	2.50
	G_T, HT (800)	3	3	2.40
	G_L	2	2	2.70
11C	G_T, HT (800)	3	3	2.40
	G_L	2	2	2.60

*G_L, ground longitudinally; G_T, ground transversely; HT (400), heat treated at 400° C for 1 h in a vacuum; HT (800), heat treated at 800° C for 1 h in a vacuum; L, diamond lapped.

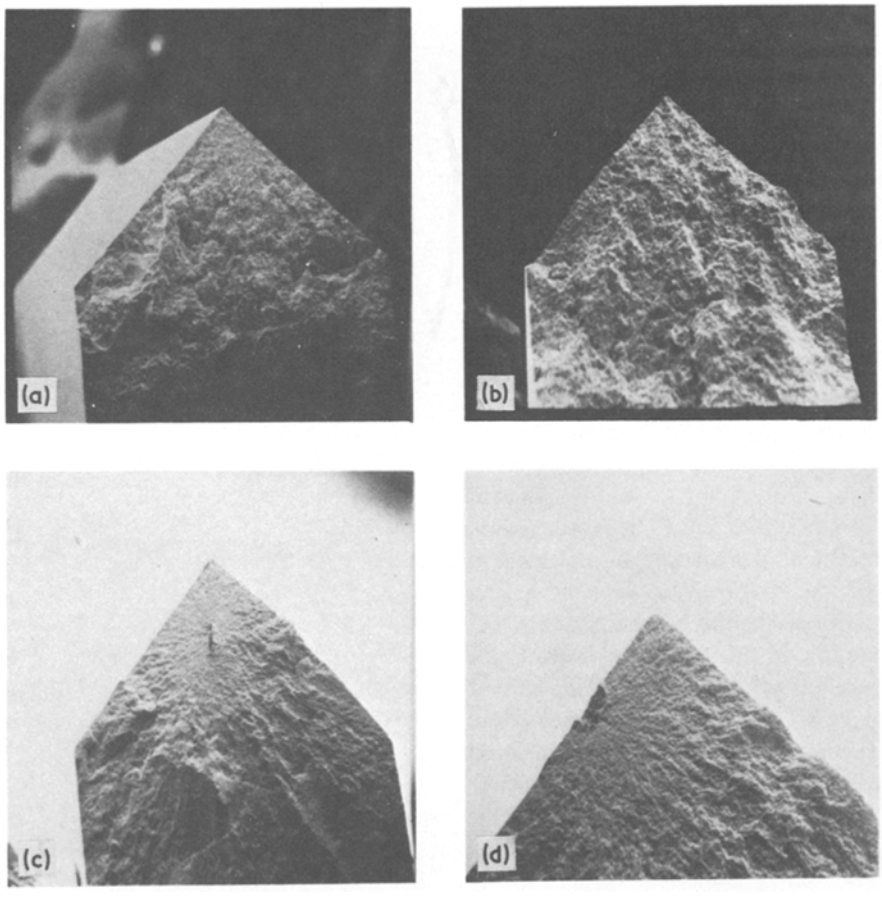

Figure 2 (a) 11F as-received, microstructure-initiated failure from apex of chamfered region (× 35); (b) 9C as-received, microstructure-initiated failure from apex of chamfered region (× 35); (c) 9F as-received, defect-initiated failure (× 35); (d) 9F as-received, defect-initiated failure (× 65).

a value for the limiting strength. Almost all the specimens of the coarse-grained hardmetals and about 70% of the specimens of the fine-grained hardmetals gave strength values which corresponded to the limiting strength. There was about 5% variation in the limiting strength values within each batch. Typical scanning electron micrographs of the fracture faces are shown in Fig. 2. Figs. 2a and b, respectively, show microstructure-initiated failures from the apex of the chamfer in a fine-grained and a coarse-grained specimen. Figs. 2c and d show defect-initiated failures in fine-grained specimens. Fractography was used on each specimen to confirm that the limiting strength values were obtained from specimens where fracture was microstructure-initiated from the apex region.

The effect of surface preparation of the apex region was studied in detail on a number of specimens of 6C prepared in different ways. The results are summarized in Table III. Surface preparation was thought to be important because the most highly stressed volume of material was situated in the apex region close to the surface. Previous work [5] had indicated that a heat-treatment of at least one hour at 800° C was necessary to relax completely residual stresses introduced by grinding. Table III shows that a value of about 2.60 kN mm^{-2} was obtained for the limiting strength of the as-ground specimens and that this value was not altered by a heat-treatment of one hour at 400° C but that it was lowered to a value of about 2.20 kN mm^{-2} by a heat treatment of one hour at 800° C. The limiting strength of 2.2 kN mm^{-2} for the ground and heat-treated specimen agreed closely with the value of 2.1 to 2.2 kN mm^{-2} obtained from the conventional bend specimens. Consequently, the tests on ground specimens probably produce a limiting strength value which is an over-estimate of the true

value because of the presence of compressive stresses introduced into the surface layers by grinding. The microstructures of the hardmetals used for this work were unlikely to be altered by the heat-treatment of one hour at 800° C, but microstructural changes can occur in hardmetals produced with a low carbon content where heat-treatment procedures can result in precipitation of Co_3W in the binder-phase [6]. Consequently, some care would be required in the interpretation of tests on low carbon hardmetals if an annealing treatment was used to remove residual stresses.

Lapping provides an alternative method to annealing for removing residual stresses, but to study the effect of lapping the specimen shape had to be modified. The simplest way of altering the shape to enable the specimens to be lapped was to reduce the height of the rectangular end sections of the chamfered specimen to a new height, $W(1-p)$. Batches of chamfered test pieces of 6C, f, g and h modified in this way were tested in the following condition: as-ground, ground and lapped, and ground and heat treated at 800° C for one hour (Table III). The limiting strength values were again calculated using Equation 4. The results obtained from these specimens were independent of the surface treatment, and all the tests gave similar limiting strength values of about 2.6 kN mm^{-2}. An explanation for this inconsistency, which might be associated with the reduced end-sections, will require further work to examine fully the lapping procedure as a means for removing residual stresses.

The results of the tests on 6C indicated that a heat treatment of 800° C for one hour in a vacuum was a reliable way of removing residual compressive stresses introduced by grinding. Table IV shows strength values obtained on chamfered specimens of 6F, 9F, 11F, 9C and 11C in the as-ground and ground and heat-treated conditions. The variation in limiting tensile strength values obtained for each batch of specimens generally was only about 5% provided that failure was microstructure-initiated from the apex region of the chamfered portion of the specimen. Most of the results obtained from the bend tests are summarized in Fig. 3 which indicates that the minimum values of the limiting strength measured on the heat-treated chamfered specimens were similar to those measured on the ground and lapped conventional test-pieces. The minimum value probably represents a true measure of the tensile strength of defect-free hardmetal,

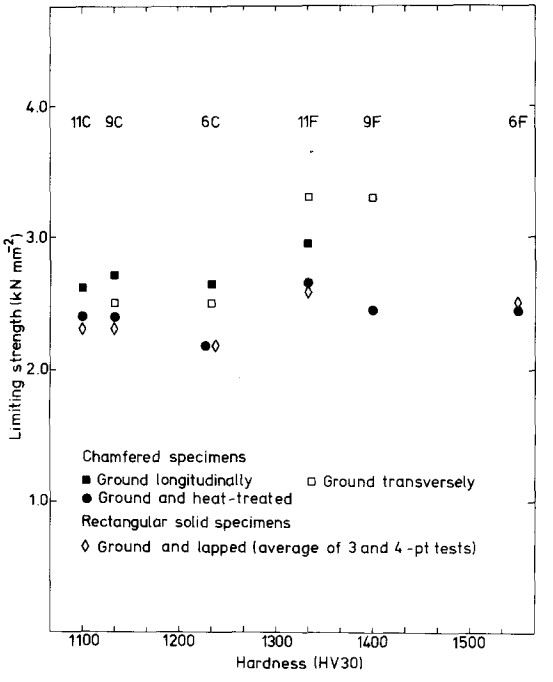

Figure 3 Limiting strength versus hardness for both chamfered and plain rectangular bend-test specimens of 6F, 9F, 11F, 6C, 9C and 11C.

the higher values being caused by the residual compressive stresses introduced into the surface during grinding.

The results of the limiting strength tests shown in Fig. 3 indicate that the true tensile strengths of 6F, 9F, 11F, 6C, 9C and 11C were similar and covered only a small range of 2.2 to 2.6 kN mm^{-2}. Previous measurements [7] of the tensile strength of hardmetals on conventional tensile test-pieces resulted in substantially lower values of 1 to 1.5 kN mm^{-2}. The low strength values obtained with conventional tensile test-pieces were probably due to fracture initiating from defects since the large highly stressed volume in such test pieces would be almost certain to contain a defect big enough to initiate fracture at a nominal stress lower than the limiting strength.

The similarity of the limiting strengths of such a wide range of hardmetals could partly be due to the effects of plasticity which were neglected in the stress calculations. Compression tests [8] on these materials indicated that for the fine-grained specimens a stress of 2.5 kN mm^{-2} produced negligible plastic strain, and hence the limiting strengths of these materials were probably equivalent to their true tensile strength. However, a stress of 2.2 kN mm^{-2} in the coarse-grained

materials produced about 0.05% plastic strain which indicated that the calculated stress overestimated the true stress. Compression tests [8] on 6C, 9C and 11C indicated that at similar strain values the true tensile flow stress corresponding to a calculated elastic stress of $2.2\,kN\,mm^{-2}$ would probably be about $2.0\,kN\,mm^{-2}$. Consequently, the effects of plasticity in the bend test tend to increase the apparent strength of the more ductile coarse-grained materials. Thus, more discriminative strength tests could be made on hardmetals if measurement of both stress and strain could be taken into account.

The results shown in Fig. 3 also indicate that grinding introduces residual compressive stresses into the surfaces of the specimens and that the effect is larger in the harder fine-grained hardmetals. Thus, in some applications a grinding treatment could increase the effective tensile strength of a hardmetal component, particularly if it was made from fine-grained carbide, by introducing residual compressive stresses into the surface.

6. Conclusions

A new bend test-piece shape has been devised which can be used to measure the limiting strength of hardmetals, which is probably equivalent to the tensile strength. The strength value obtained from this test is determined by the microstructure and is not dependent on the defect content. Thus the results of the test can be used to assess the effects of metallurgical variables such as microstructure on the mechanical properties of different hardmetals. A particular benefit of the test is that relatively few specimens are needed since even for the more brittle fine-grained materials, on average, at least 3 out of 5 specimens would give a limiting strength value and would not fracture from internal defects.

The principle of the test of reducing the highly stressed volume in the specimen to minimum might equally well be applied to other materials of low ductility where bend tests have been used previously to measure strength, since conventional tests can often result in a wide spread of strength values because of the predominance of defect-initiated failures. The use of a chamfered test-piece should reduce the scatter and provide a mechanical property measurement related to the microstructure and so be more suitable for comparing the tensile strengths of different materials.

In order to obtain a true value for the tensile strength it is essential to relieve grinding stresses introduced during specimen preparation and this can be done by a subsequent heat-treatment of 800° C for one hour in a vaccum. A lapping treatment might also remove residual stresses but further experiments are needed to explain the inconsistent results produced on the lapped specimens with reduced end-sections.

A grinding treatment can increase the apparent tensile strength of the surface regions of hardmetal test-pieces; consequently it might prove to be practically useful to surface grind some hardmetal components.

Appendix

Stress formula for the chamfered bend specimen

The width, w, of the specimen in Fig. 1 is given by

$$w = B \quad \text{for} \quad 0 \leqslant x \leqslant W(1-p)$$

and

$$w = \frac{B}{p}\left(1 - \frac{x}{W}\right) \quad \text{for} \quad W(1-p) \leqslant x \leqslant W$$

where x is the distance measured from the base of the specimen in a vertical direction.

Therefore the total area of the specimen, A, is given by

$$A = BW\left(1 - \frac{p}{2}\right) \tag{A1}$$

The total moment of the cross-section about the base, M_b, is given by Ae, where e is the distance between the neutral axis and the base, and also by

$$M_b = \int wx\,dx$$

Therefore

$$Ae = \int_0^{W(1-p)} Bx\,dx + \int_{W(1-p)}^{W} \frac{B}{p}\left(x - \frac{x^2}{W}\right)\cdot dx$$

$$= \frac{BW^2}{6p}\left[1 - (1-p)^3\right] \tag{A2}$$

The moment of inertia of the cross-section about the base ($x = 0$), I_0, is given by

$$I_0 = \int wx^2\,dx = \int_0^{W(1-p)} Bx^2\,dx + \int_{W(1-p)}^{W} \frac{B}{p}\left(x^2 - \frac{x^3}{W}\right)dx$$

$$= \frac{BW^3}{12p}\left[1 - (1-p)^4\right] \tag{A3}$$

The moment of inertia about the neutral axis (from the parallel axis theorem) I, is given by

$$I = I_0 - Ae^2 = I_0 - \frac{(Ae)^2}{A}$$

$$= \frac{BW^3}{12}\,\frac{1-(1-p)^4}{p} - \frac{3(1-p+p^2/3)^2}{1-p/2}$$

$$= \frac{BW^3}{12}\,\frac{1-2p+2p^2-p^3+p^4/6}{1-p/2} \qquad \text{(A4)}$$

Thus the section modulus, Z, from Equations A1, A2 and A3 are given by

$$Z = \frac{I}{(W-e)} = \frac{BW^2}{6}\,\frac{1-2p+2p^2-p^3+p^4/6}{1-p^2/3}$$

Consequently the maximum tensile stress, σ_T, is given by

$$\sigma_T = \frac{M}{Z} \qquad \text{where } M \text{ is the bending moment}$$

$$\sigma_T = \frac{3PL}{BW^2}\,\frac{1-p^2/3}{1-2p+2p^2-p^3+p^4/6} \qquad \text{(A5)}$$

where P is the load at failure, L is the distance between the inner and outer loading points in the 4-point bend rig and $2L$ is the span of the 3-point bend rig.

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