
Biaxial Flexure Testing of Single layer and Bilaminar Discs

4.1 Introduction

In the previous chapter crowns were tested to establish the cracking pattern and loading capacity of the bilaminar system used to construct In-Ceram crowns. The results indicated a variety of cracking modes with the principal ones being the formation of a cone crack, delamination of the bilaminar structure and radial cracks. It was also apparent that the cone crack appeared first but did not always directly cause the complete failure of the crown. Subsequent development of radial cracks caused the complete failure of the crown.

The first step in this section is to establish the behaviour of In-Ceram® and Vitadur Alpha® under flexural conditions. The flexural condition was chosen because during normal loading conditions in the mouth teeth undergo a degree of flexure, and by their very nature, crown preparations produce a tooth support structure (dentine) that is more flexible than the ceramic crowns used to restore them. The ceramic restorations undergo a degree of flexure (strain) at the point of occlusal contact. This could be likened to a hard and brittle coating over a ductile substrate. The results from chapter 3 indicate possible improvements to fracture resistance by changing the core to veneer thickness ratio. Figure 3.17b demonstrates a crown with an increased core thickness and which required a higher load to produce the initial failure. They also indicate fracture from both a Hertzian cone crack with a second crack coming from within the ceramic core material and fracturing the whole crown. Both are the result of tensile stresses. The International Standard, ISO 6872 for Dental Ceramic, part 8.3.2 details a biaxial flexure test protocol, which enables examination of the tensile properties of the ceramics as they might be expected to experience in the mouth. This test is similar to the one proposed in 1980 by Marshall. The specimen size used in this standard is comparable to the sizes found in dental crowns.

In the preparation of In-Ceram all ceramic crowns the manufacturer's instructions indicate a core to veneer thickness ratio of 1:1 with approximate thicknesses of 0.5 mm for each layer. The experience from chapter 3 where an initial group of 25 crowns were made using

the paint on technique for slip application indicated that the average core thickness was 0.588 mm and the average veneer thickness was 0.604 mm. The result was an overall average thickness of approximately 1.2 mm. This is within the thickness ranges given for the ISO standard.

It should also be noted that crowns have varying thicknesses according to their position in the dental arch, their role in the occlusion and the point at which occlusion occurs with the antagonist tooth. It is also important to allow for the taper of the preparation which will mean that some parts of the crown have several millimetres of ceramic in some form before the dentine is encountered. An example is the ceramic in a proximal area of any tooth.

The replacement of tooth structure with ceramic presents an interesting mechanical situation because there is a large discrepancy in the stiffness of the component parts and the order in which they are used. In the tooth the harder and stiffer layer (enamel) is on the outside and it is supported by the relatively flexible dentine on the inside. The In-Ceram crowns have their stiffest layer below the outer layer. The stiffness of the outer layer is similar to enamel, but the anatomy is very different. The enamel is constructed of individual hydroxy apatite crystals lying parallel to one another and designed to be orientated with their axes in the direction of any subsequent loading. The porcelain veneer consists of feldspathic crystals supported by a brittle glass matrix. The very stiff In-Ceram ceramic core material provides a base resistant to flexure to prevent the Vitadur Alpha veneer porcelain from flexing and exceeding its critical strain limit. A comparison of tooth and ceramic data can with respect to Young's modulus can be seen in table 4.1.

Table 4.1 Comparison of selected physical properties for tooth structure and the dental ceramic for this study.

	Flexural Strength (MPa)	S.D. (MPa)	Modulus of Elasticity (GPa)
Tooth Structure: Enamel			*65
Tooth Structure: Dentine			*15
In-Ceram® †	495.52	37.38	287.3
Vitadur Alpha® ‡	62.0	10.8	70

- Sources: *Tooth structure - Swain (1994)
 † In-Ceram - Ironside (1995)
 ‡ Vitadur Alpha - Ironside (unpublished data)

The strength values for In-Ceram® are similar to those reported by Magne et al., (1997). However the test methods were different, Magne used In-Ceram beams in a three point bend test.

The intention in this chapter is to observe the behaviour of bilaminar discs tested according to the ISO standard for dental ceramics and determine whether the results correspond to those found in the crown tests. Finite Element Analysis will be used to map the stress distributions found in the discs as they are loaded. The inclusion of dentine in the Finite Element Analysis gives data from within the support continuum and is indicative of how support from tooth structure and glass ionomer influences the flexural behaviour of the ceramic. The Young's modulus of glass ionomer is similar to dentine.

4.2 Materials and Methods

Bilaminar discs were constructed from In-Ceram® and Vitadur Alpha in two thicknesses and diameters. The specification of each group appears in table 4.2. The discs were tested for flexural strength tests using ISO 6872 where a flat punch of 1.6 mm diameter is used to load the disc specimens while they are supported by three steel balls equidistantly placed in a circle of 5 mm radius. The cross-head speed for all tests was 0.5 mm per minute. Further simulated load tests using both the flat punch and 5 mm spherical indenter under Finite Element Analysis conditions were conducted to compare with the in vitro crown data reported in Chapter 3 and the ISO biaxial tests in this chapter. This was done to confirm the continuity between all testing regimes to maintain clinical significance.

4.2.1 Specimen preparation

One hundred and twenty In-Ceram discs were prepared with the slip-casting technique, according to the manufacturer's recommendations. All the discs were used to test strength. Sixty disks were made with a 12 mm diameter and either a 0.5 or 1 mm thickness. Sixty discs were made with a diameter of 16 mm and a thickness of either 1 or 2 mm. The 12 x 0.5 mm group and the 16 x 1 mm group had Vitadur Alpha porcelain layers fired to their top surfaces, according to the manufacturer's instructions. The construction and firing schedules appear in appendix II. Two further groups of discs (n=30) were constructed of Vitadur Alpha. One group had dimensions of 12 mm diameter and 1 mm thick; and the other was 16 mm in diameter and 2 mm thick. All six groups appear in table 4.2. The decision to use discs of 12 mm diameter and a 1 mm thickness was because these dimensions more closely resemble the actual dimensions involved with

anterior crowns. This is with reference to the thickness in particular, whereas the choice for the larger discs as per the ISO standard was to establish continuity between the larger dimensions and the expected results. That is could the ISO model for the discs provide information that could be related to the dimensions of the crown. It should also be noted that the crown dimensions given are for anterior crowns, but that the suggested protocol for posterior crowns required an increased core thickness for the expected heavier loads.

All specimens were shaped by placing an open-ended silicone mould on a base made from the special plaster die material, (Ironsides 1993). The In-Ceram alumina slip was poured into the mould and dried before sintering in a high temperature furnace (In-Ceram II, Vita Zahnfabrik, Bad Säckingen, Germany). The sintering temperature was 1120° C. After sintering the specimens were milled flat using a diamond milling burr in a dental milling machine/parallelometer. Final surfacing for smoothness and thickness was achieved by hand rubbing on carborundum paper of 600-grit size. The carborundum paper was supported on flat glass slabs to ensure the flattest possible surface. The thickness was checked using a digital micrometer. The specimens were then infused with the special lanthana based infiltration-glass. The glassy slurry was placed onto the top of the disc, which was then placed on special platinum/gold alloy foil. In doing so, the air was free to escape through the other surface. The excess glass was removed by sandblasting with 110 μm Al_2O_3 at the maximum pressure of 5 Bar. The presence of the glass was checked with a further firing and, where necessary, removed with a sandblaster using 50 μm Al_2O_3 at 2 Bar. The specimens were then ground with diamond discs of nominal grit 120, 70, 30 and 15 μm to the final dimensions (1 mm thick x 12 mm diameter, and 2 mm thick x 16 mm diameter).

The application of the Vitadur Alpha porcelain was facilitated by inserting a finished In-Ceram disc into a silicone rubber ring at a depth equal to the thickness of the disc. The porcelain slurry was then added to the disc using the traditional brush technique used to add porcelain to crowns in their normal build-up process. The disc and porcelain were removed from the ring and placed in the furnace and fired at 960°C. Following cooling after the firing cycle the disc had a preliminary trim using a cylindrical diamond bur in a dental laboratory handpiece. The disc was returned to the ring and further porcelain added to correct deficiencies caused by shrinkage during the vacuum firing process. After this correction firing the discs were ground to size in a customized diamond wheel grinder that was designed to mill the top porcelain surface parallel to the bottom In-Ceram surface. The grinder had a fine stage height adjustment to allow a few μm at a time to be removed. This precaution was taken to reduce the risk of crack formation from the process. The grinding was performed under water to reduce heat production. When the overall thickness was at the correct height, the discs were coated with glaze (Vitachrom Delta

740) and refired at 940°C according to the manufacturer’s instructions. The discs were given a final check for imperfections and then tested. Following the tests, two additional groups were constructed, (n=10) as a preliminary indicator for design change direction. These groups were also 16 mm in diameter and 2 mm thick but they had intermediate bilaminar constructions, i.e. one group had In-Ceram : Vitadur Alpha 1.5 ; 0.5 and the other had the reverse ratio, 0.5 : 1.5. The results for the 16 mm diameter groups appear in table 4.5

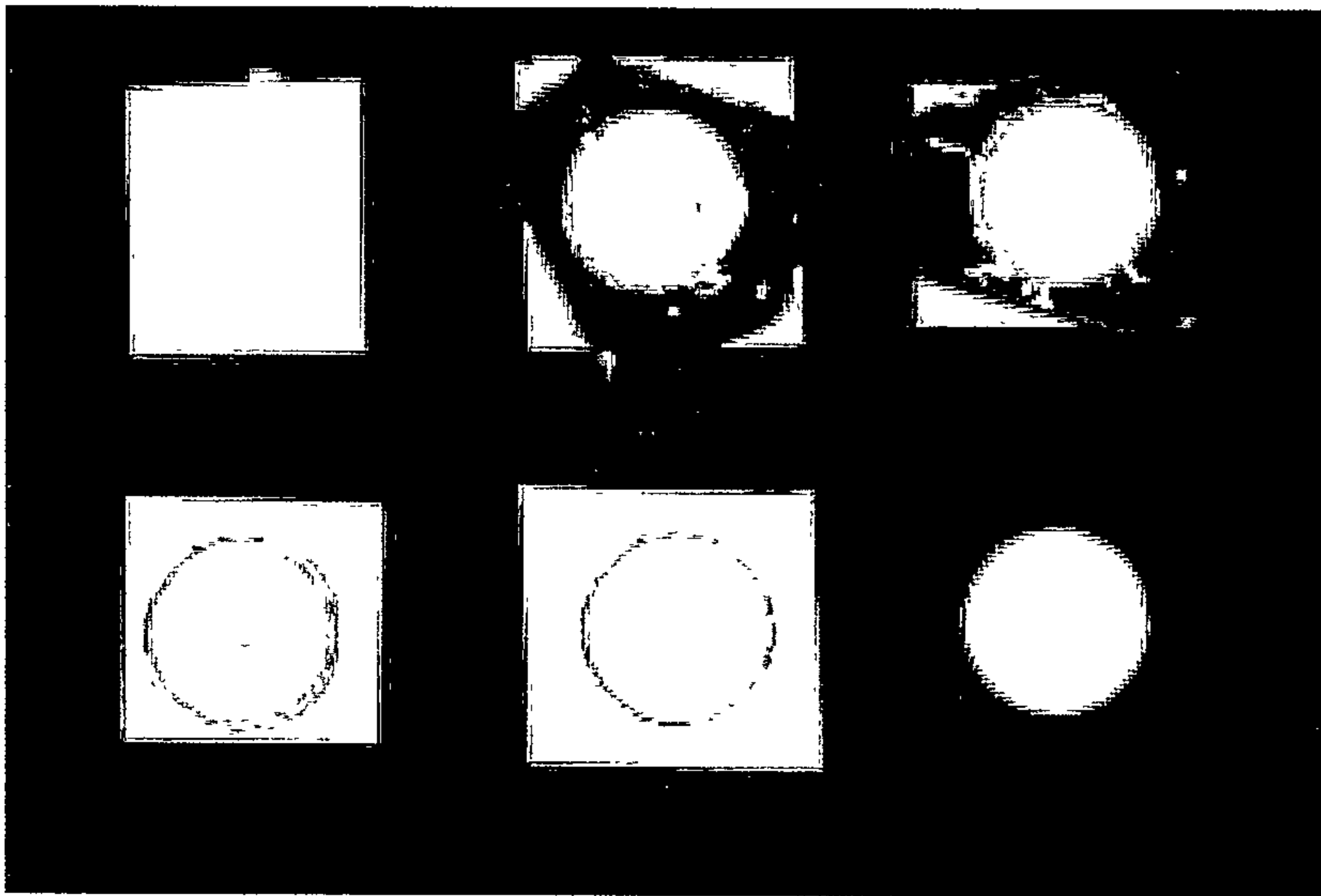


Figure 4.1 *(Top L to R)* Special plaster base; special plaster base and silicone ring to form mould; Wet In-Ceram® slip in mould.

(Bottom L to R) Silicone slip removed from dried slip; In-Ceram® disc after sinter fire; final In-Ceram® disc ready for glass infiltration.

Table 4.2 Preliminary ceramic test groups.

Disc Diameter	Thickness
12 mm (n = 30)	1 mm - In-Ceram
16 mm (n = 30)	2 mm - In-Ceram
12 mm (n = 30)	1 mm - (0.5 mm In-Ceram & 0.5 mm Vitadur Alpha)
16 mm (n = 30)	2 mm - (1 mm In-Ceram & 1 mm Vitadur Alpha)
12 mm (n = 30)	1 mm – Vitadur Alpha
16 mm (n = 30)	2 mm - Vitadur Alpha

4.2.2 Biaxial Testing

The discs were subjected to a punch on three ball testing protocol, i.e. bi-axial tensile test with a crosshead speed of 0.5 mm per minute. This style of testing has been advocated by Southan et al., (1973), Marshall (1980) and Ban et al., (1990) and forms the basis of ISO Standard 6872 part 8.3.2. The punch diameter was 1.6 mm and the diameter of the support balls was 3.2 mm. The support balls for all tests were placed on the periphery of a circle with a radius of 5 mm. The support balls and punch were made of hardened steel. The flexural strengths of the homogenous materials to be tested were also recorded using expressions 4.1, 4.2 and 4.3:

$$S = -0.238(7P(X - Y))/d^2 \quad (4.1)$$

X is given by the equation:

$$X = (1 + \nu) \ln(r_2/r_3)^2 + [(1 - \nu)/2](r_2/r_3)^2 \quad (4.2)$$

Y is given by the equation:

$$Y = (1 + \nu) \left[1 + \ln(r_1/r_3)^2 \right] + (1 - \nu)(r_1/r_3)^2 \quad (4.3)$$

Where

S is the maximum centre tensile stress in megapascals;

P is the total load causing fracture, in Newtons;

ν is Poisson's ratio. If the value for the ceramic concerned is not known, use Poisson's ratio = 0.25;

r_1 is the radius of the support circle, in millimetres;

r_2 is the radius of the loaded area, in millimetres;

r_3 is the radius of the specimen, in millimetres;

d is the specimen thickness at fracture origin, in millimetres.

A photograph of the testing rig appears in the figure 4.2 below. An opened out picture in figure 4.3 demonstrates the three support balls and the end of the flat punch. Figure 4.4 shows the actual end of the punch. The tests were conducted in a Shimadzu Autograph universal testing machine shown previously in figure 3.13.

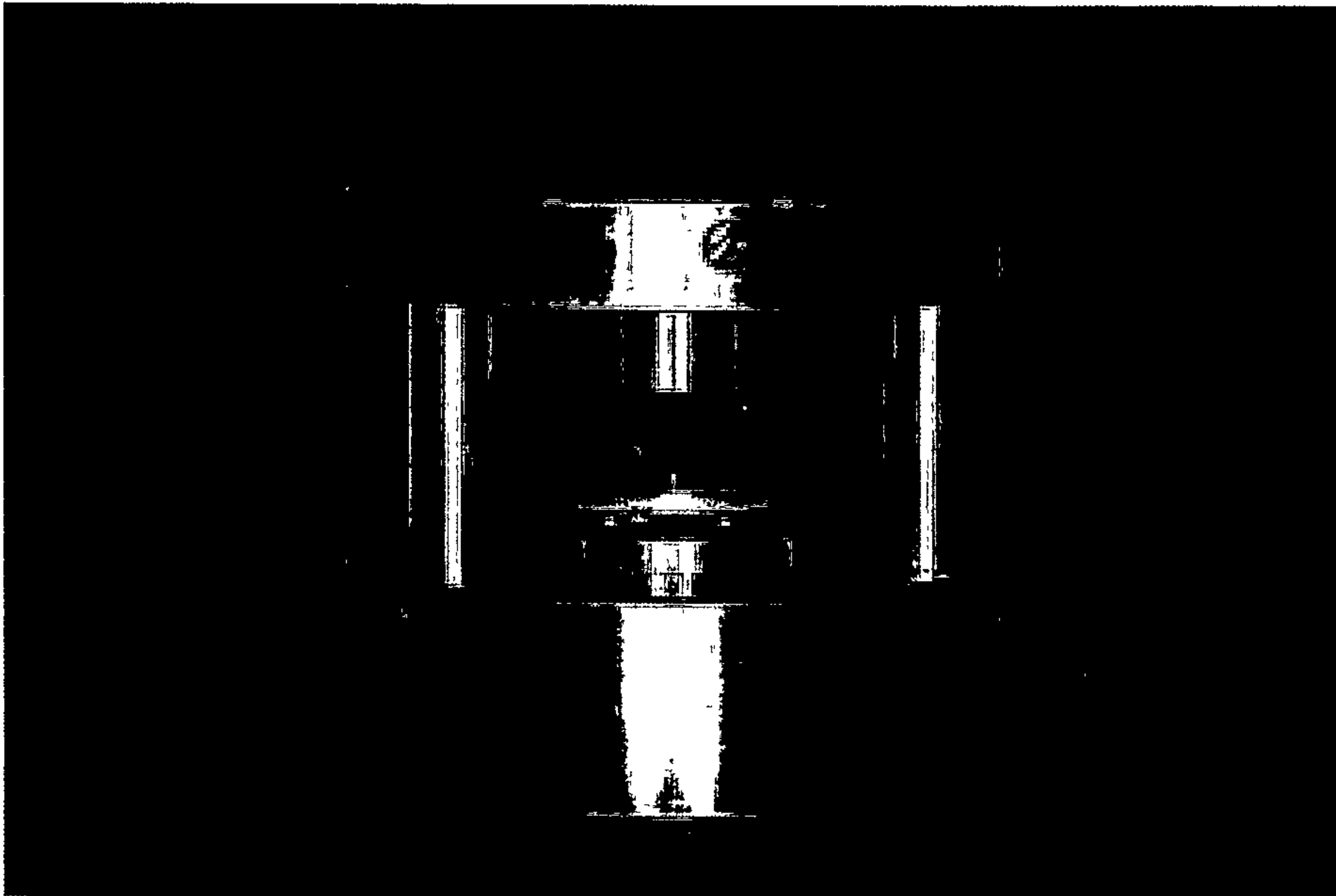


Figure 4.2 This figure demonstrates the rig used to support the disc and guide the punch down onto the specimen. The rig itself was placed between the upper and lower mounts of the universal testing machine with the load cell located in the moveable cross member. This was driven down onto the rig to provide and record the load, i.e. the test rig was placed in compression.

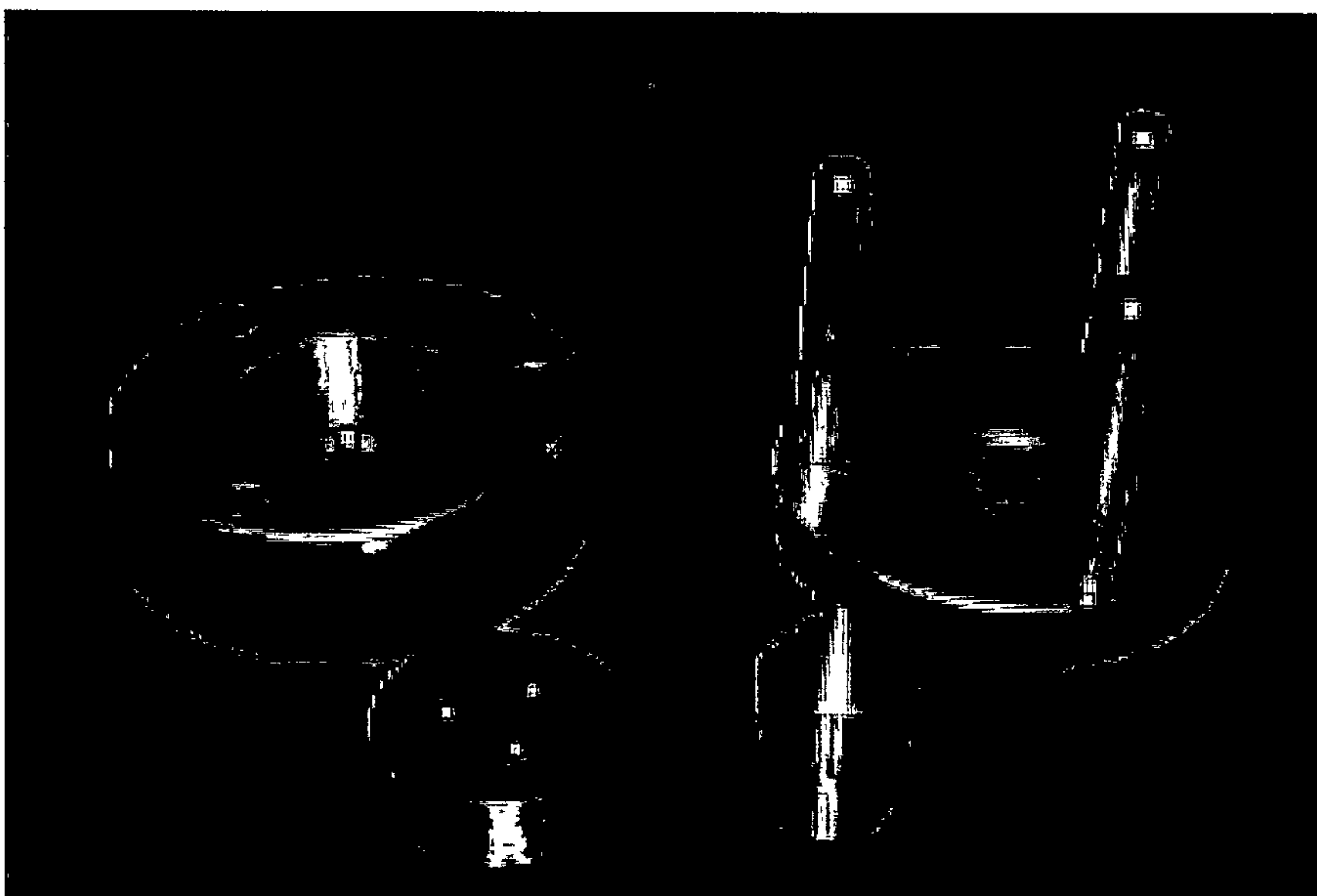


Figure 4.3 The components of the flexural test rig. The lower brass base for the guiding rods and the steel base with the three balls are on the left and the flat punch and the upper brass base with the guide rods is on the right.

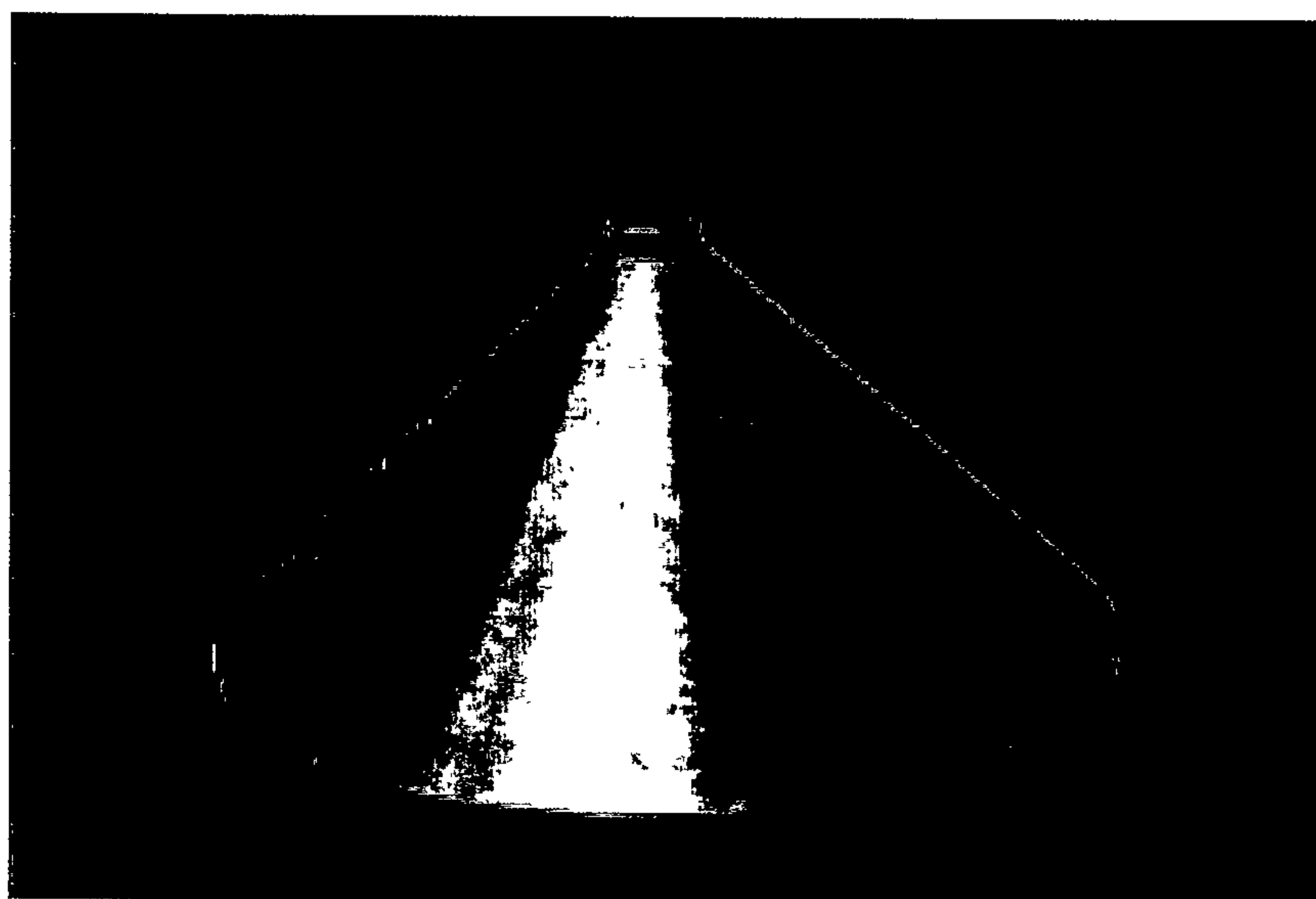


Figure 4.4 The 1.6 mm diameter end of the flat steel punch.

When the 1.6 mm diameter flat steel punch, is applied vertically downwards at the centre of the disc, stresses result from the overall pressure. There are compressive stresses directly beneath the punch on the top surface of the disc and tensile stresses both on the undersurface and just outside the periphery of the punch contact area. The magnitude of the contact stresses for the punch are much lower than for a sphere as the radius of contact is much larger.

Table 4.3. Material Properties of Biaxial disc components

Property	Young's Modulus E (GPa)	Poisson's ratio
Vitadur Alpha	70	0.28
In-Ceram Alumina	287	0.22

4.2.3. Finite Element Analysis

Five different axisymmetric models were made of the biaxial disc. Each model had a radius of 8 mm, and a thickness of 2 mm. Each model was varied by changing the ratio of the Vitadur Alpha to the In-Ceram Alumina. Axisymmetric Finite Element Analysis (FEA) used axisymmetric plate elements. For each model, 1600 of these plate elements were used. The different thickness combinations used for the five models were: 2.0:0.0; 1.5:0.5; 1.0:1.0; 0.5:1.5; 0.0:2.0. (Ironside et al., 2001)

4.2.3.1 Ring supported biaxial test, flat piston load.

All models had the same vertical loading, directed downwards. It was a 2D element plate edge pressure of 746 N/mm^2 applied to the top edge of 8 elements. This simulated a flat piston load of 1500 N uniformly distributed over a radius of 0.8 mm.

The FEA modelling for the biaxial test used a complete ring rather than three ball support. The three-ball support is used mechanically to allow for any planar imperfections that might occur in a disc during manufacture. A perfectly flat disc would be required on a ring to prevent any non-uniform stresses localities.

At a distance 5 mm from the centre vertical axis, a constraint was applied simulating a ring support. The loading and constraint can be seen in figure 4.5. It is for the disc with a 1.0:1.0 ratio of Vitadur Alpha to the In-Ceram Alumina.

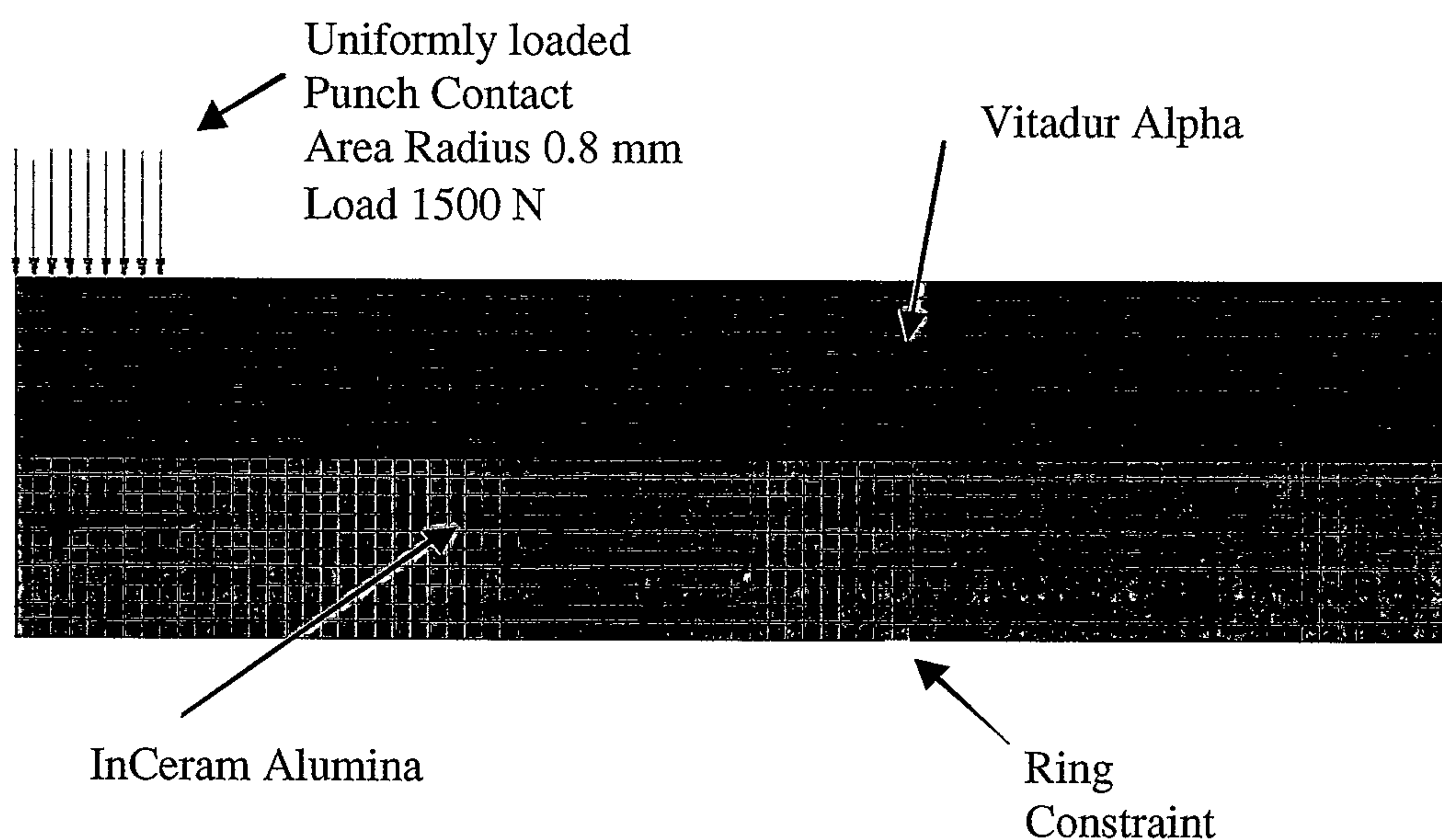


Figure 4.5. Axisymmetric plate element model of biaxial disc with loading conditions and constraints for punch loading on ring support. Ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

4.2.3.2 Ring Support below Biaxial Disc 5 mm Ball Load

For the case of loading the biaxial disc with a 5 mm diameter ball (0.3 mm contact radius), three different axisymmetric models were made. Each model had the same external dimensions as those used for the piston load. Three different thickness combinations of Vitadur alpha to In-Ceram Alumina were used for each model: 1.5:0.5; 1.0:1.0; and 0.5:1.5. Their properties are noted in Table 4.3 above.

All models had the same vertical loading, directed downwards. However, a semicircular load pattern was applied to the edge of three elements, to simulate a ball indenter. To the element closest to the centre of the disc, an edge stress of 4944.2 N/mm^2 was applied. Edge stresses of 4342.6 and 2771.8 N/mm^2 were applied to the second and third elements respectively. This simulated a hemispherical load of 1000 N applied over an area of radius 0.3 mm .

At a distance 5 mm from the centre vertical axis, a constraint was applied simulating a ring support. The loading and constraint can be seen in Figure 4.6. It is also for the disk with a $1.0:1.0$ ratio of Vitadur Alpha to the In-Ceram Alumina.

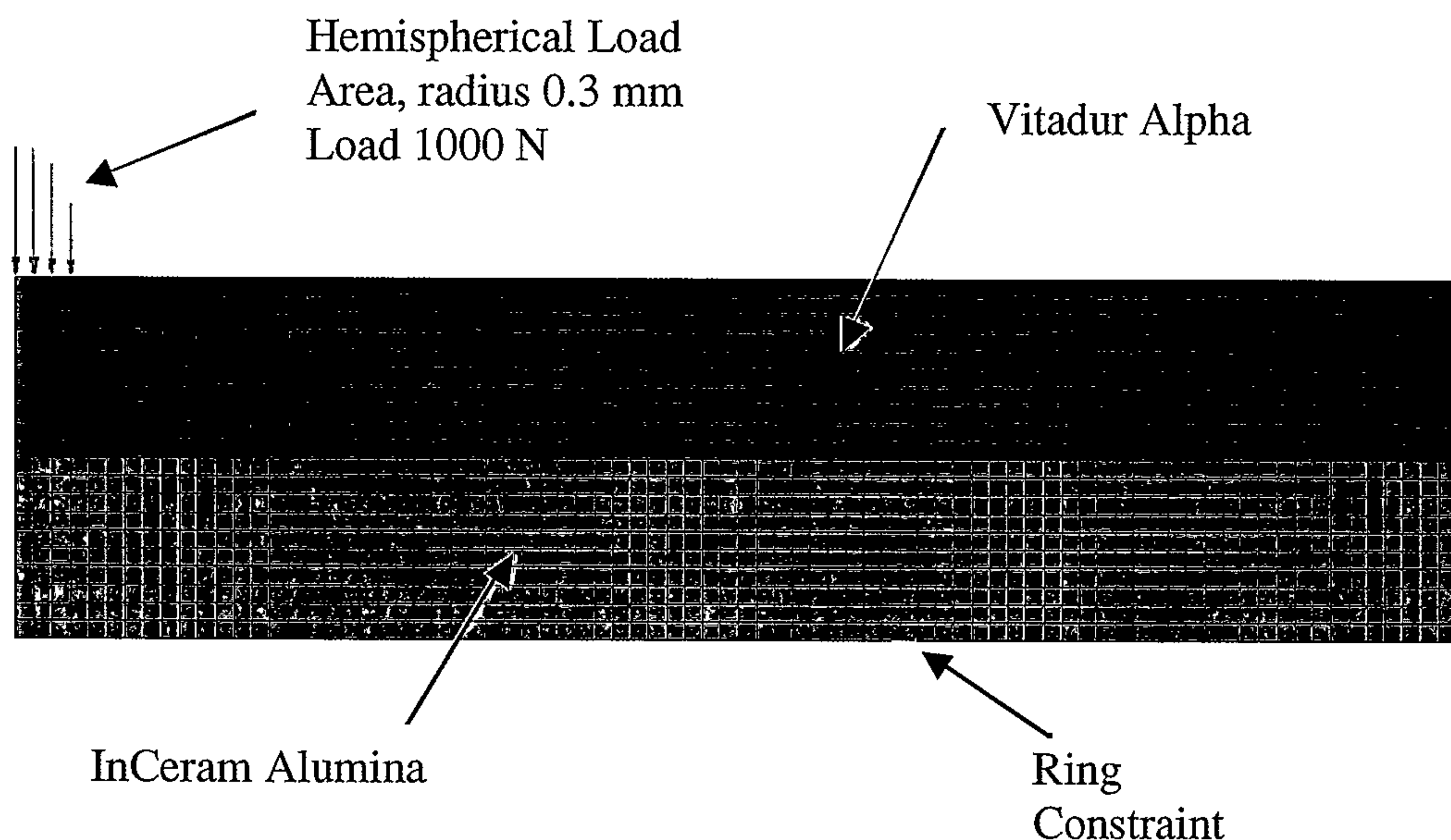


Figure 4.6. Axisymmetric 2D element model of biaxial disc for ball loading on ring support. Ratio of Vitadur Alpha to In-Ceram Alumina $1.0:1.0$.

4.2.4 Weibull Statistics

Failure/reliability will be assessed using Weibull statistics. Plots and moduli for the different groups will be recorded and compared to give an indication as to which could be the strongest and most reliable designs under flexure.

4.3 Results

4.3.1 Mechanical Testing

The results of the mechanical testing of the preliminary group are given below in table 4.4. The results indicate little difference between the two model sizes and justify the use of the ISO standard disc dimensions for further modelling. The failure loads for the bilaminar discs are of the same order as those experienced with the crown tests and those that could be expected from the biting forces in table 3.4.

Table 4.4. Bi-axial flexural strength and failure loads for In-Ceram, Vitadur Alpha and In-Ceram/Vitadur Alpha bilaminar discs.

Disc: Diameter, Material (Thickness)	Flexural Strength MPa	Load at Failure Newtons
16mm In-Ceram (2mm)	495	1851
12 mm In-Ceram (1mm)	476	530
Vitadur Alpha (2mm)	63.9	226.9
Vitadur Alpha (1mm)	62.8	56.4
16mm Bilaminar (2mm)	243	916
12mm Bilaminar (1mm)	272	239

The bilaminar strength was calculated from equation 4.1. The correct value of the stress was also calculated using Finite Element Analysis and will be reported in the following FEA sections. The results for the bilaminar specimens where the In-Ceram was under tensile loading appear to be considerably underestimated. This is more evident when the results in group 2, of table 4.5 are considered.

Table 4.5 In vitro failure loads for In-Ceram/Vitadur Alpha discs according to changes in thickness ratios and using piston on three ball biaxial test.

Group No.	In-Ceram to Vitadur Alpha Ratio (mm)	Average Failure Load: Newtons	Flexural Strength: MPa (SD)
1	2.0 : 0.0	1851	495 (37.4)
2	1.5 : 0.5	948	254(19.3)
3	1.0 : 1.0	916	243(33)

4	0.5 : 1.5	912	244 (11.8)
5	0.0 : 2.0	226.9	63.9 (11)

4.3.2 Examples of Crack Patterns

The initial crack appears to be from the indentation on the top surface where the load is concentrated via the punch or the indenter over a relatively small area as seen in figures 4.7 and 4.8. However a second crack system appears on the underside of the specimen, figure 4.9, and appears to be more like a radial crack starting from the outer surface. The use of fractography by optical observations could not determine the origin of the crack on the underside due to the high crystalline nature of the In-Ceram layer. The discs in the following three figures are the same disc. The series is from a group using the spherical indenter, because it was not possible to stop the crack process when using the punch on three ball technique. The crack patterns are the same as those reported by Rhee et al., (2001).



Figure 4.7. The spherical indentation on the top surface of a bilaminar ceramic disc
This disc was tested using a ball indenter and three-ball support.

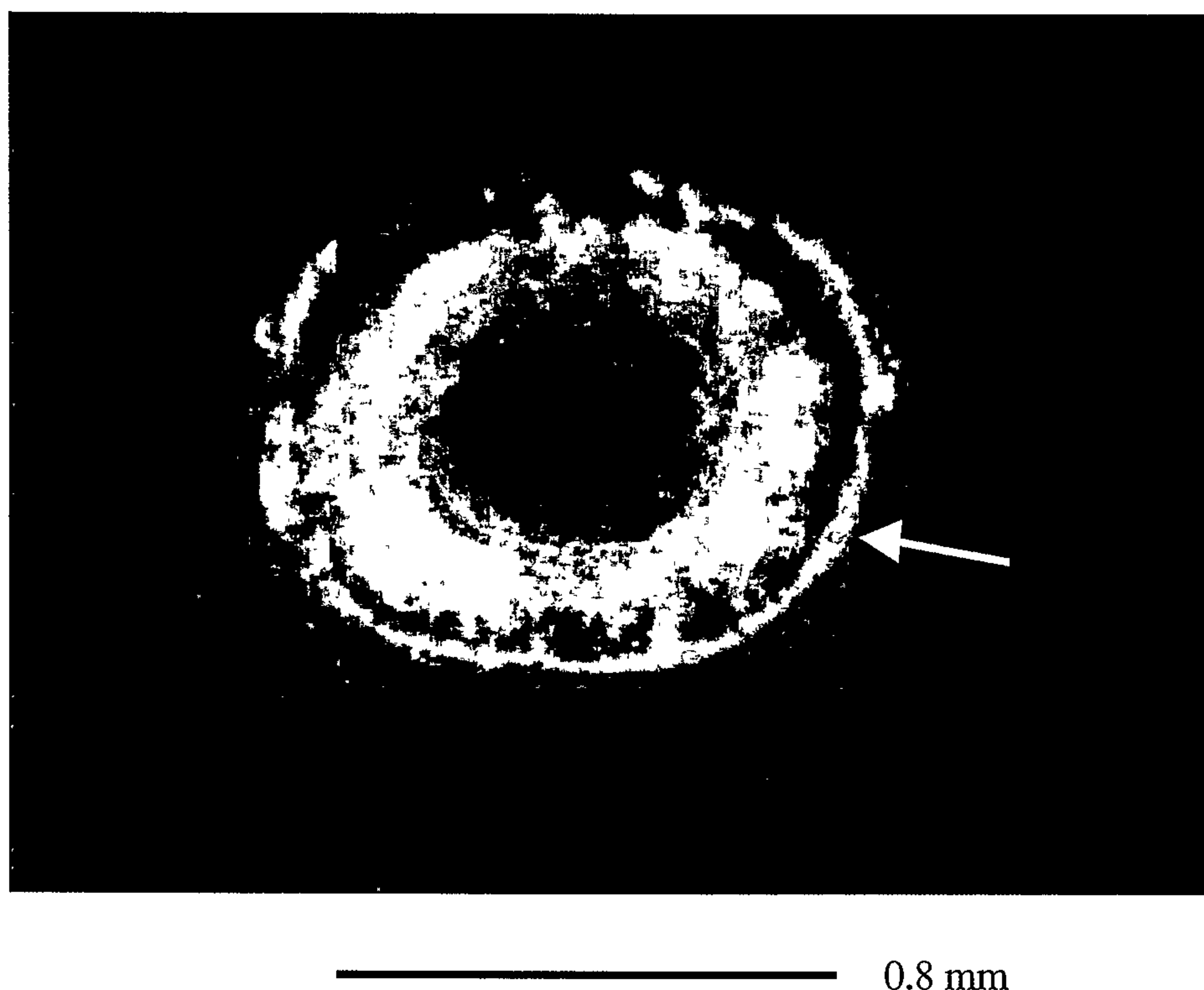


Figure 4.7. A closer view of the spherical indentation on the top surface of a bilaminar ceramic disc. The arrow marks the Hertzian cone crack.

The spherical indentation on the top surface of a bilaminar ceramic disc in figure 4.6 above can be seen more easily in the following close-up, figure 4.7. The important aspect of this photograph is the series of concentric circular cracks that are typical of this type of indentation. The sharper outer circle is the classic surface ring crack feature of the Hertzian cone crack.

The under side of the disc developed the beginnings of a radial crack, which can be seen in figure 4.8 below. There is a longer crack and a second crack not clearly evident in figure 4.8 but initiating orthogonal to the main crack. Ultimately all of the discs failed due to these radial cracks and there was a trend that the higher failure loads were associated with multiple radial cracks with the discs shattering into many pieces. Discs that failed at a low load generally broke into two pieces only. The latter failure result also raises the question that a major flaw could have been introduced during the processing stage. The manufacturer's instructions for In-Ceram specifically call for a die test after machine adjustments (grinding with dental laboratory burs) of the sintered alumina framework. The blue die highlights any cracks by leaving a concentrated blue line.

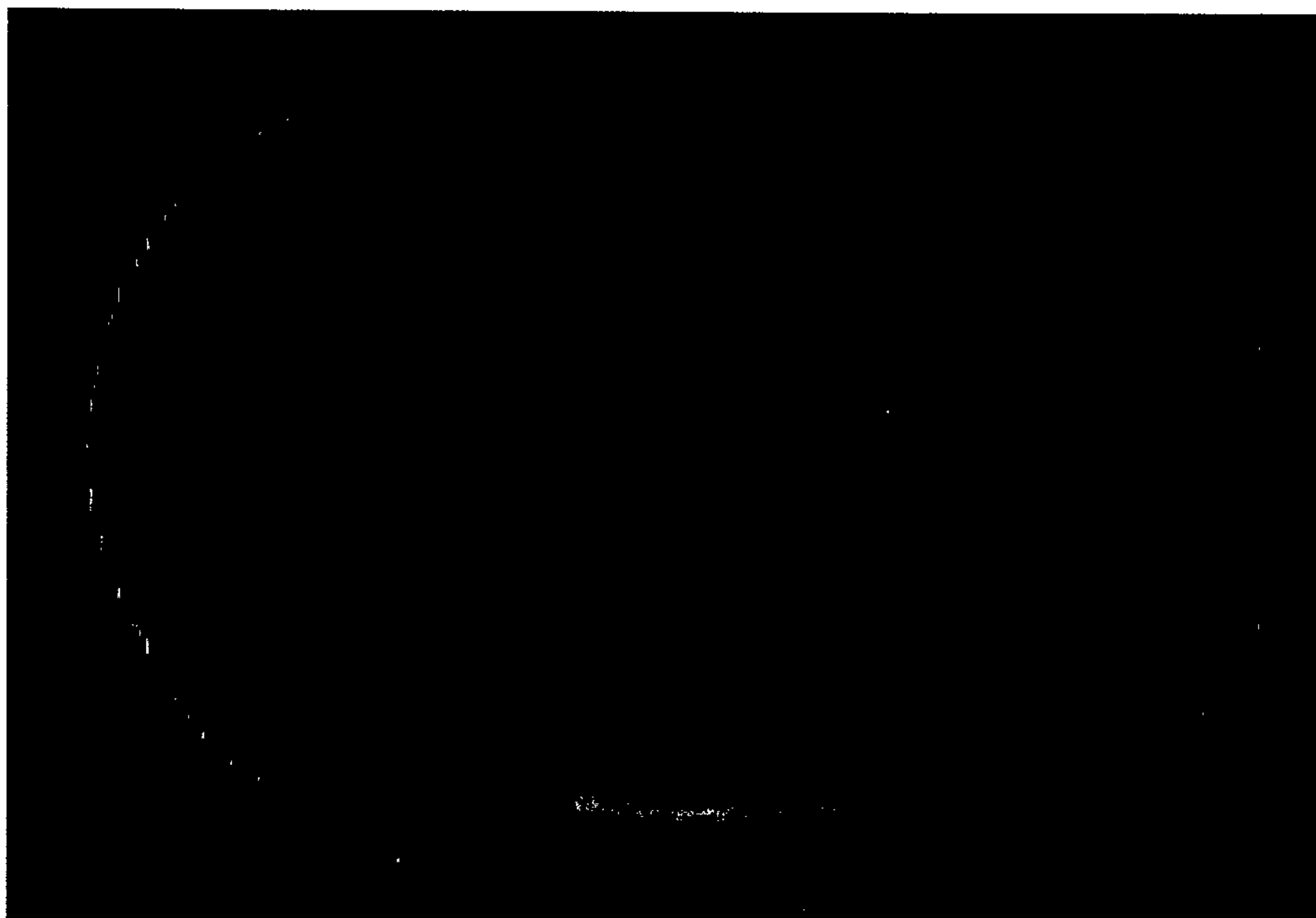


Figure 4.8 The under side of the disc developed with the beginnings of two radial cracks at approximate right angles.

Most discs tested under biaxial loading failed completely and the opportunity to observe the beginnings of crack formation were not available.

4.3.3 Results from the Finite Element Analysis.

4.3.3.1 Ring supported biaxial test, flat piston load.

The following finite element models demonstrate the intensities of the stresses within the disc during flexural loading applied by a flat punch. The top surface can be seen undergoing compression and the bottom surface undergoes tension. The interface undergoes a mild degree of compression as could be expected because the veneer layer has a lower Young's modulus and therefore the level of strain allows some compression at that point. The example in figure 4.10 demonstrates the overall distribution for the cross-section of a disc in the Z axis. The left side of the diagram is the centre of the disc and the right side is the periphery. The radius of the loaded area is 0.8 mm. This view highlights the concentration of stresses at the central portion of the disc. Figure 4.11 gives a more detailed view of the central area. The peak tensile stress on the undersurface is given as 843 MPa and the peak compressive stress on the top surface is given as 756 MPa. A compressive stress in the top portion of the In-Ceram layer caused by the strain in the

Vitadur Alpha layer is in the region of approximately 200 MPa. Under these conditions this middle stress zone would not be considered to be of any significance. A summary of the radial stresses versus their position along the Z axis is given in figure 4.12.

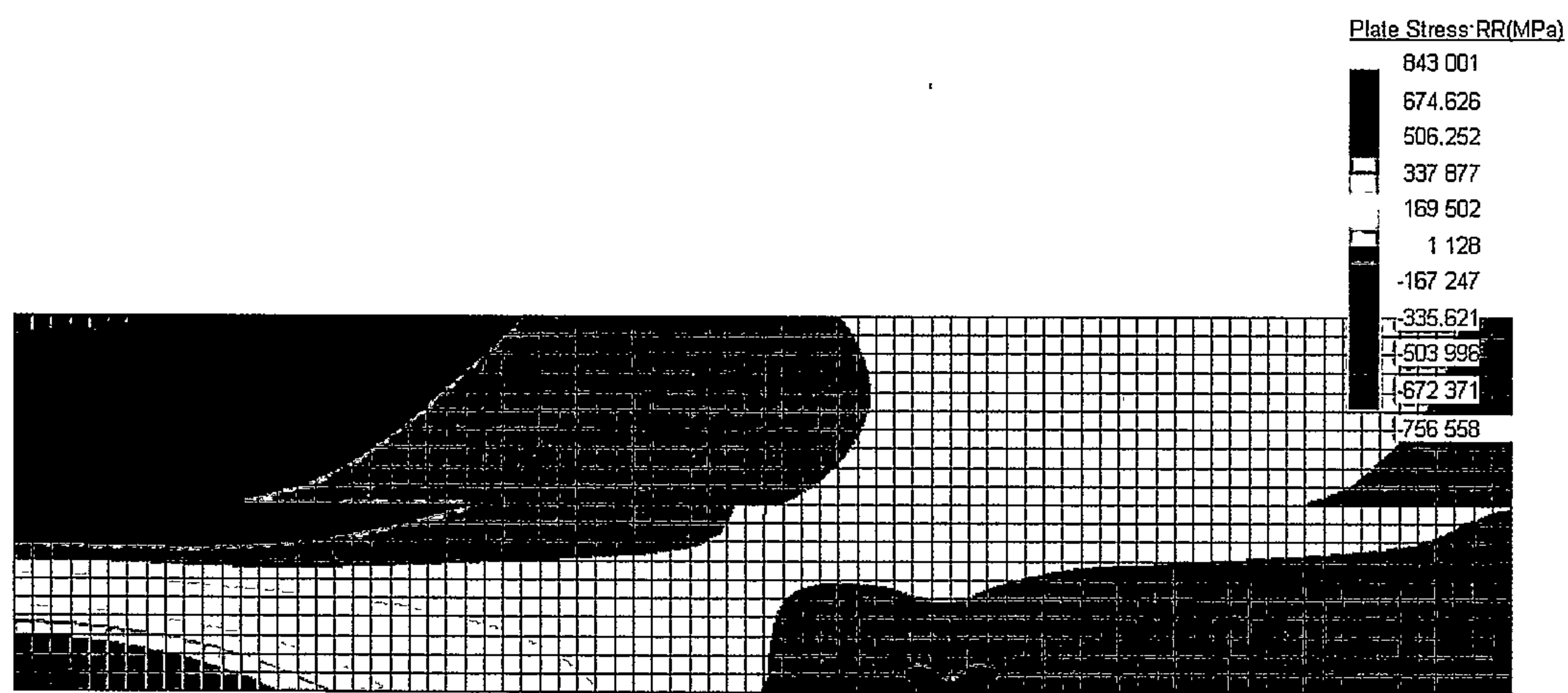


Figure 4.10. Radial Stress (MPa) of disc model for punch loading on ring base for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

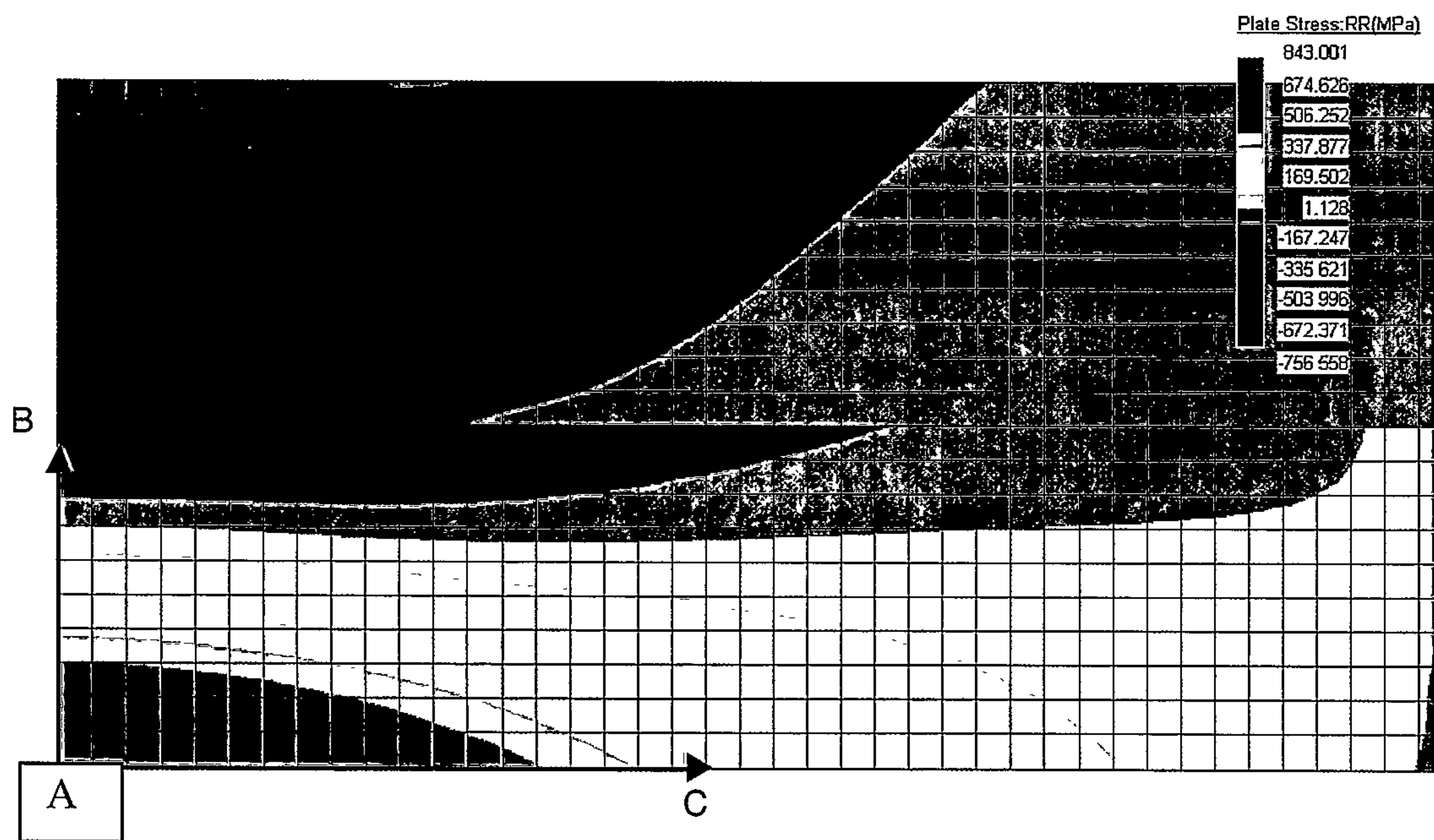


Figure 4.11. Radial Stress (MPa) of disc model centre region for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. Disc on ring base with piston loading.

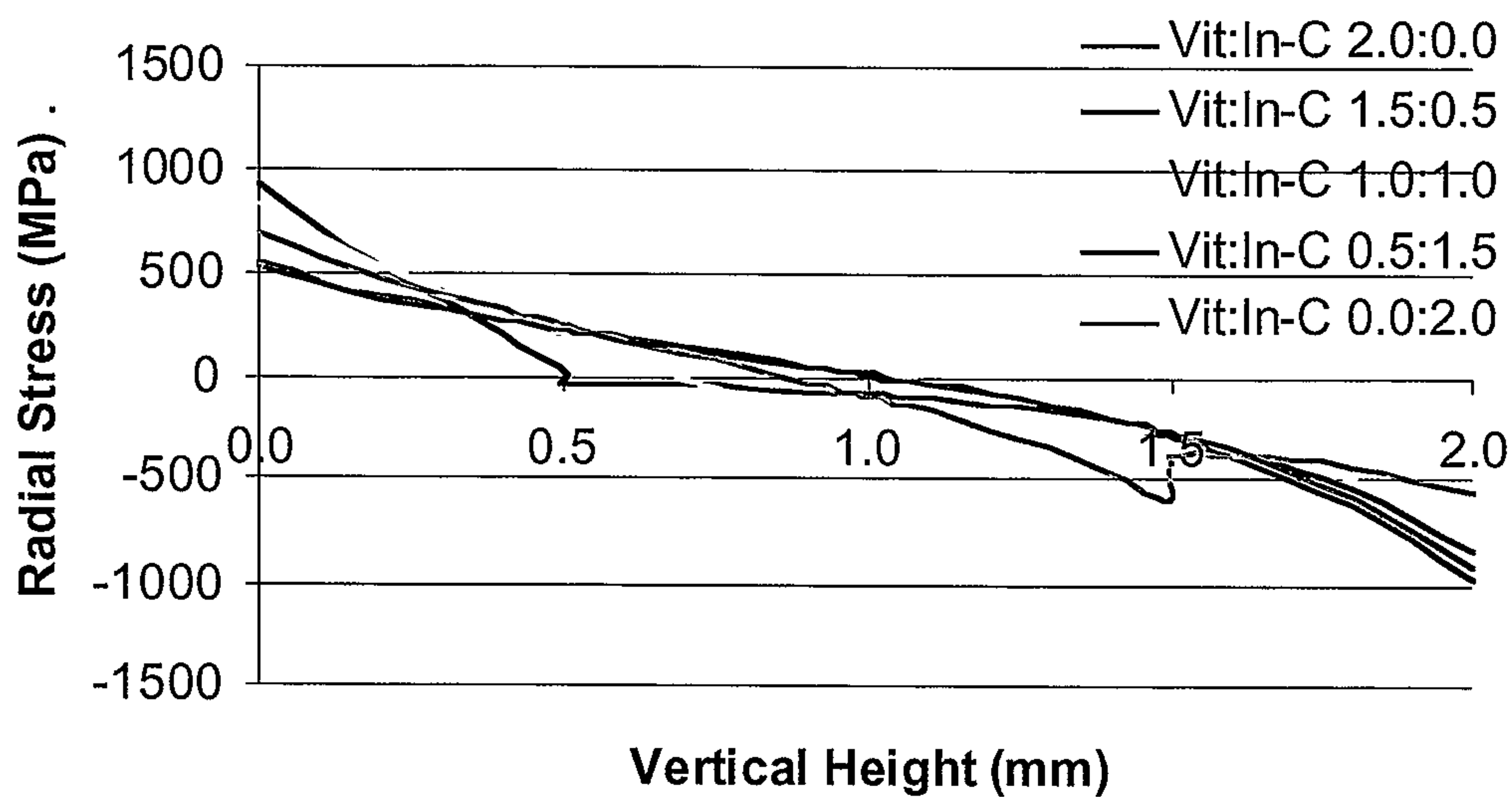


Figure 4.12 Plot of Radial Stresses for each model, ring base, piston loading. Stresses measured along the axis of symmetry from point A to point B in figure 4.11.

The radial stresses plotted in figure 4.11 indicate the influence of changing the layer ratios on the magnitude and distribution of the stresses. The two examples that were monolayered, i.e. all Vitadur Alpha or all In-Ceram, both flexed in a uniform manner as expected and generated tensile stresses on their undersurfaces. The magnitude of the stresses are in reasonable agreement with the prediction by equations 4.1, 4.2 and 4.3, the minor difference arising from the difference in Poisson's ratio between the In-Ceram and the Vitadur Alpha. The difference between them was that the In-Ceram supported a much higher load for a similar level of stress.

For the bilaminar discs the magnitude of the tensile stresses on the lower surface were in all instances higher than predicted by equations 4.1, 4.2 and 4.3. The plots of the principal stresses along the axis indicates a sharp discontinuity at the Vitadur Alpha – In-Ceram interface and a steep increase to the lower surface. As the layer of Vitadur Alpha was decreased in thickness and the In-Ceram was increased in thickness, the stresses on the top surface decreased whereas the stresses on the bottom surface increased as did the stresses at the interface.

In figure 4.13 the distribution of the tensile stresses across the bottom surface can be seen. The peak occurs in the centre as expected, with the bilaminar discs exhibiting much greater stresses than the monolithic discs. The difference in the Young's moduli and the resultant difference in the strain deformation under a given load effectively adds further tension to the stiffer In-Ceram layer. A simple view of this situation is that porcelain with the lower elastic modulus deflects much further than the higher modulus In-Ceram core.

For bilaminar discs there is a compromise with the porcelain deflecting less and the In-Ceram deflecting more than if they were the only constituents of the disc. The greater the deflection of the In-Ceram thus resulting in the higher than estimated tensile stresses from equations 4.1, 4.2 and 4.3.

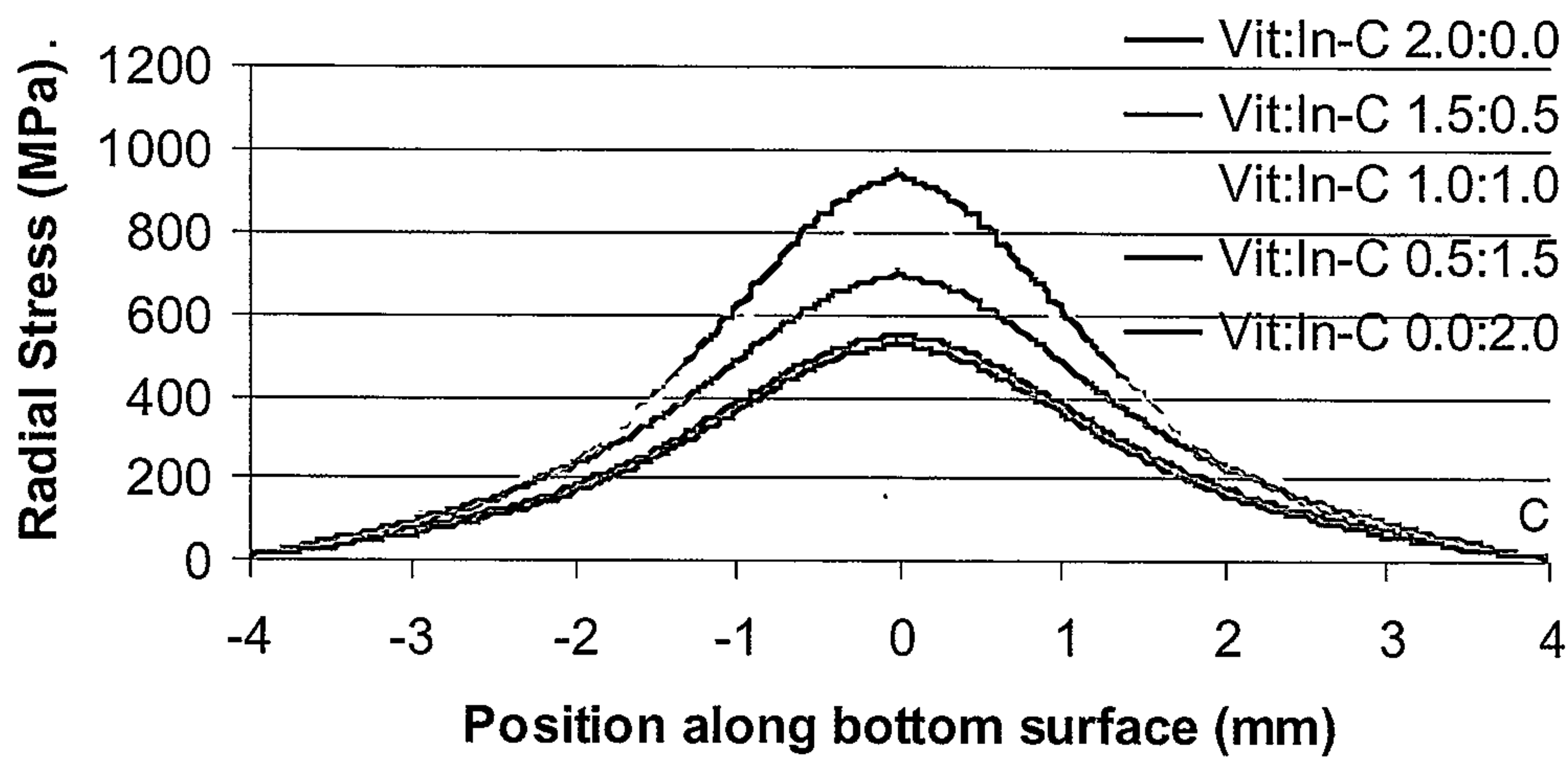


Figure 4.13 Plot of Radial Stresses for each model, ring base, piston loading. Stresses measured along the bottom of surface from point A to point C in fig 4.11.

The influence of the bilaminar construction and loading on the resultant stresses is tabulated in table 4.6. this table determines the tensile stress for 1500 N load and provides the ratio predicted by equations 4.1, 4.2 and 4.3 with the FEA analysis. The bilaminar discs all have significantly increased values.

Table 4.6 Ratio of maximum tensile radial stress for each disk ratio to the maximum tensile radial stress for Vitadur Alpha to In-Ceram Alumina 0.0:2.0.

Case	Ratio of Vitadur Alpha to In-Ceram Alumina	Maximum tensile radial stress in disc (MPa)	Ratio of FEA to Analytical Eq. 4.1 and 4.2
1	2.0:0.0	552.0	1.07
2	1.5:0.5	940.6	2.34
3	1.0:1.0	843.0	2.12
4	0.5:1.5	698.8	1.74
5	0.0:2.0	529.1	1.31

On the basis of this table, the strength values previously compared in table 4.4 are recalculated and listed in table 4.7.

Table 4.7 Recalculated Flexural Strength values for In-Ceram/Vitadur Alpha discs according to changes in thickness ratios and using punch on three ball biaxial test.

Group No.	Average Failure Load: Newtons	Flexural Strength: MPa (SD)
1	1851	529.6 (37.4)
2	948	594.4(19.3)
3	916	515(33)
4	912	424.6 (11.8)
5	226.9	83.7 (11)

The recalculated values give the bilaminates significant increase in strength which is mirrored in the Finite Element Analysis and is not in keeping with the original analytical results. The biaxial formula does not take into account the Young’s Modulus for either layer in the bilaminates. The significance of this omission becomes more obvious as the materials are tested and compared in chapter five. The stiffer lower layer in the bilaminate provides significant support to the top layer, particularly when it is also supported by a stiff foundation. Where the fusion of the two layers is complete, the constraints to deformation in the top layer are further enhanced, again improving the apparent strength.

4.3.3.2 Ring Support below Biaxial Disc 5 mm Ball Load

The introduction of this loading system provides information concerning the effect of a spherical indenter and how it compares with the flat punch. This will provide a link to the tests and FEA analysis that are reported in the following chapter. These subsequent tests are used to observe the effect of loading the discs with spherical indenters while the disc is supported by a rigid base in one series using analogue and FEA results, and by dentine in another series using FEA only. The top surface in figure 4.14 can be seen undergoing compression and the bottom surface undergoes tension. Using this model, the distribution of stresses is much more localised beneath the indenter, with very high compressive stresses below the centre of the ball.

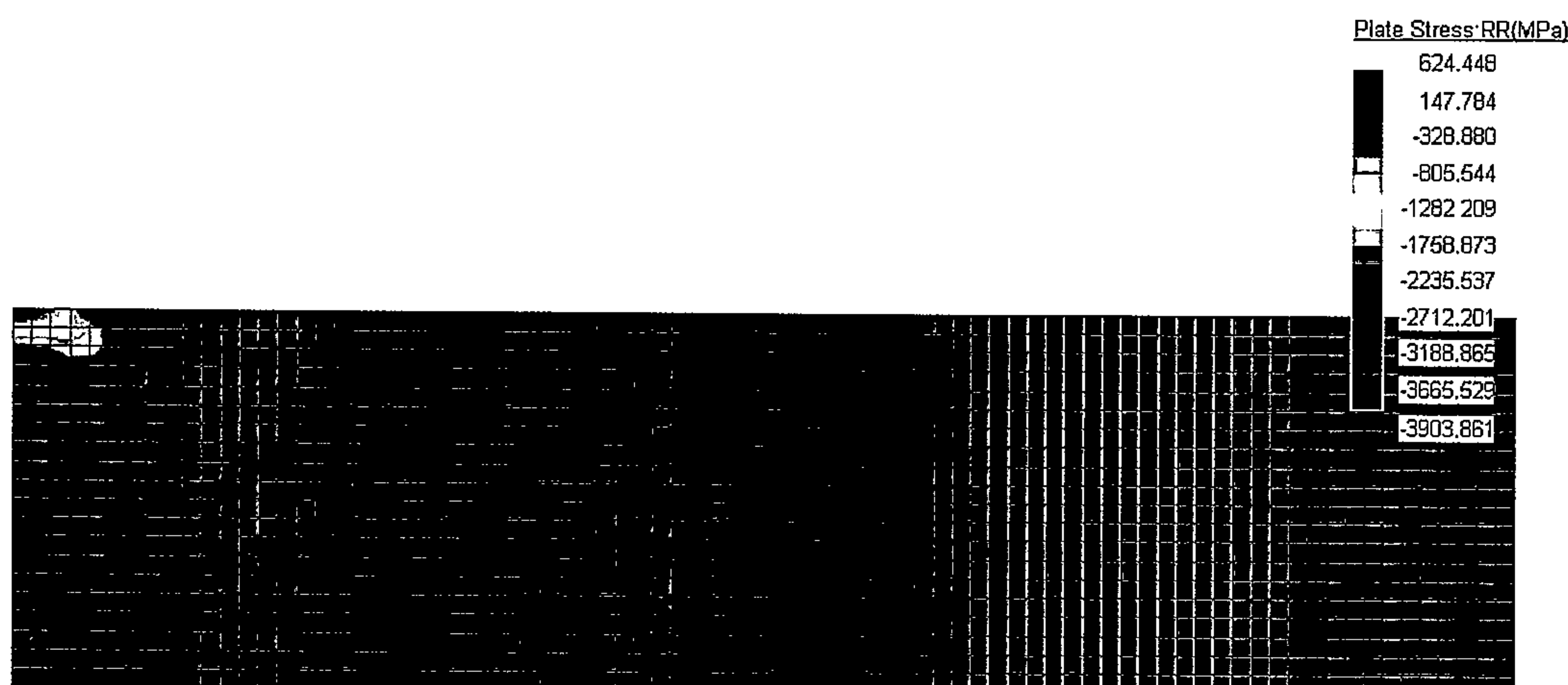


Figure 4.14. Radial Stress (MPa) of disc model, ball loading, on ring base for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

In figure 4.15 below, an expanded view reveals the high compressive stress below the indenter and the rapid change from compressive to tensile stress as the distance from the centre along the top surface is increased and the radius of the contact area is reached. This is typical of the stress distribution that would be found for the initiation of a cone crack. Below the outer edge of the third brick face element a developing gradient can be seen. The pattern of this gradient is along the line or profile of the area that a cone crack would be expected to develop and propagate. The interface can also be seen to be developing different stress patterns to those seen in figure 4.11. In this instance the stresses appear to be more tensile than compressive and according to the graph in figure 4.17 they are highest when the In-Ceram layer is at its thinnest.

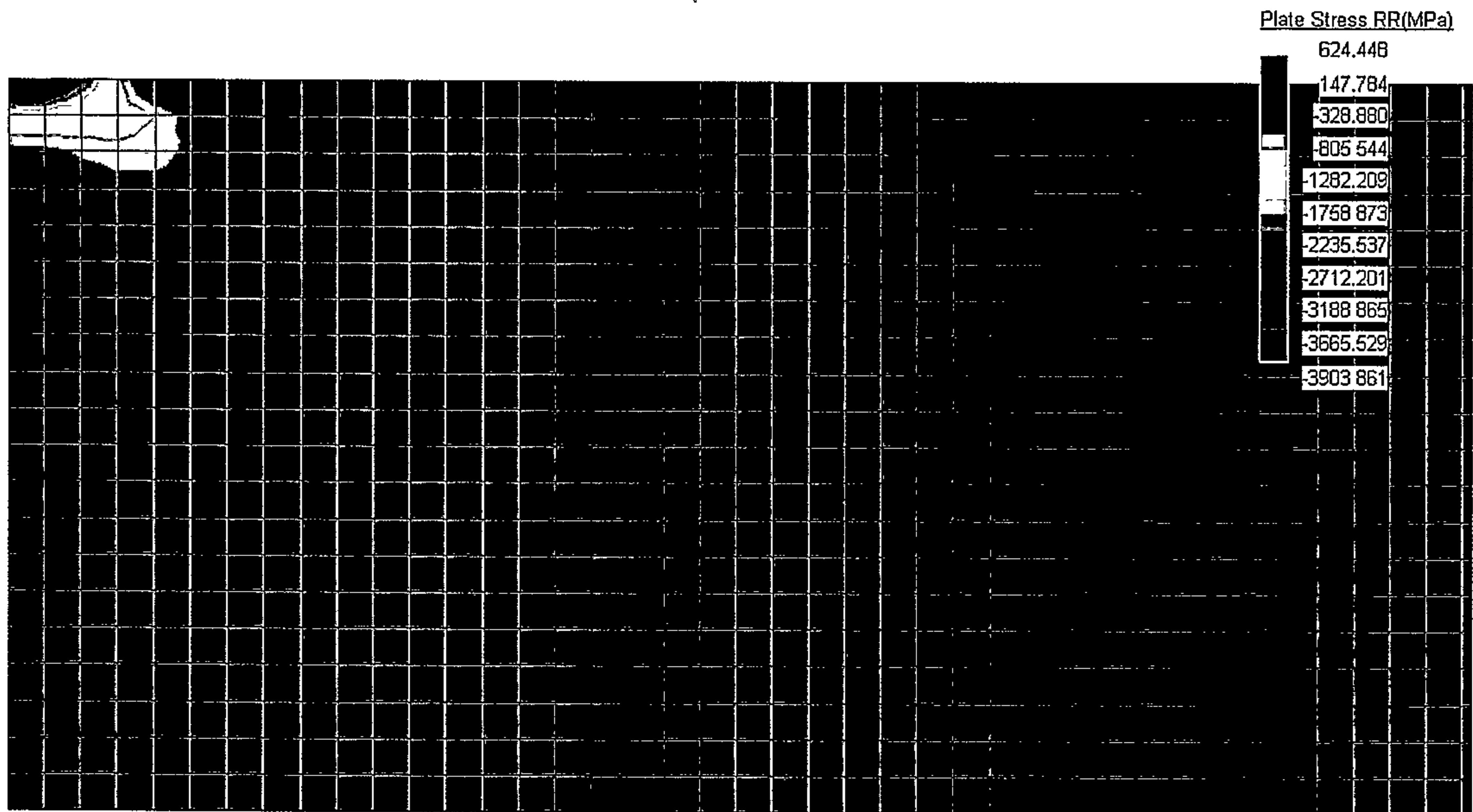


Figure 4.15. Radial Stress (MPa) of disc model centre region for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. Disc on ring base with ball loading.

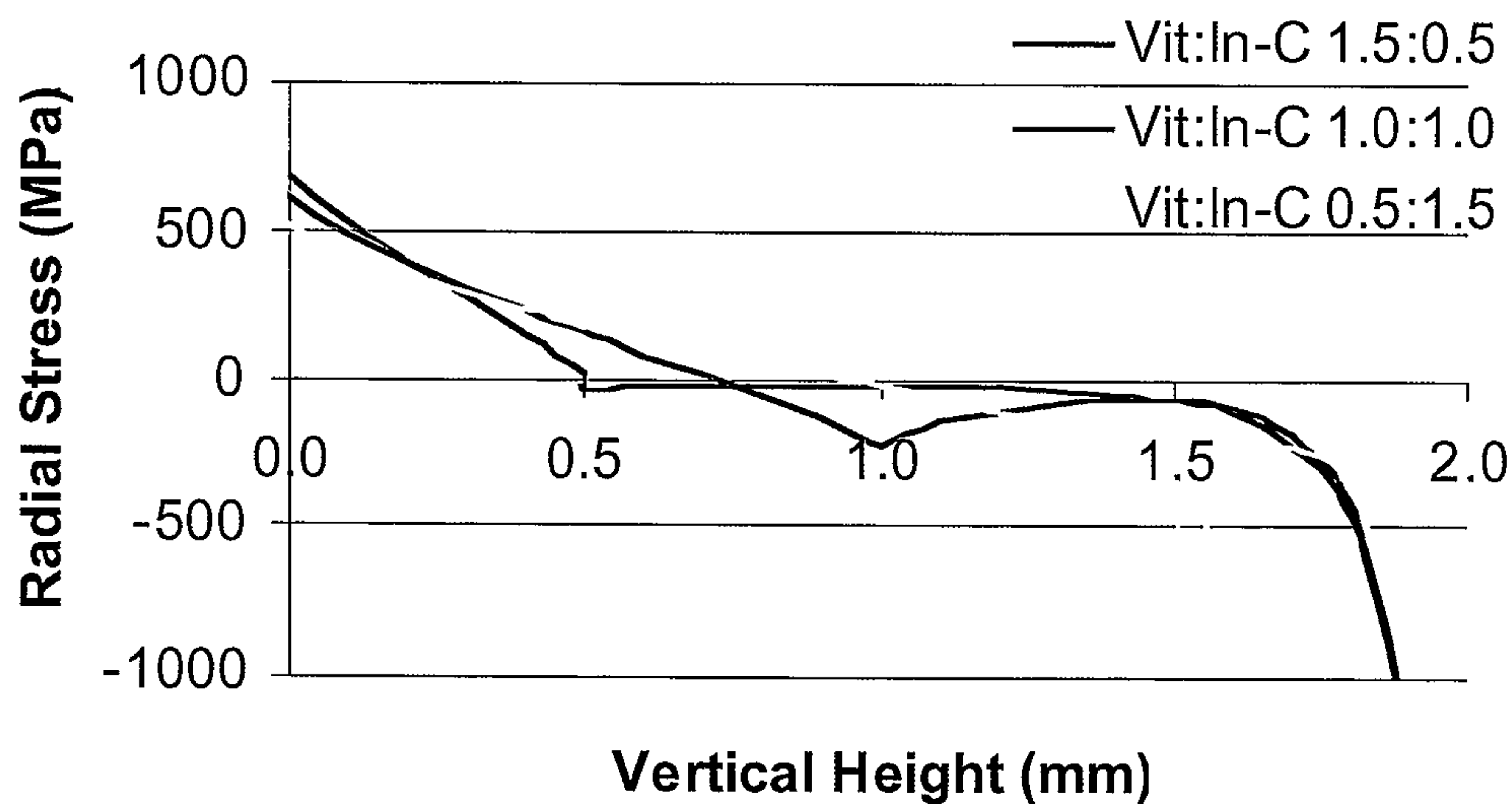


Figure 4.16. Plot of Radial Stresses for each ring support model, ball loading, with varying thickness of Vitadur to In-Ceram. Stresses measured along the axis of symmetry from the bottom surface to the top surface.

In figure 4.16 the effect of the three different bilaminar ratios can be seen. The radial stress patterns are significantly influenced by thickness of the In-Ceram. All ratios have similar stress levels on the top surface in particular, but also to a lesser degree on the bottom surface. However there is a progressive increase in stress at the interfacial

boundary as it gets closer to the indenter. The radial stresses on the In-Ceram are greatest when the Vitadur Alpha is at its thickest. This is shown in figure 4.17, where it is also noted that the higher stress levels on the bottom surface are confined to a relatively small area below the indenter

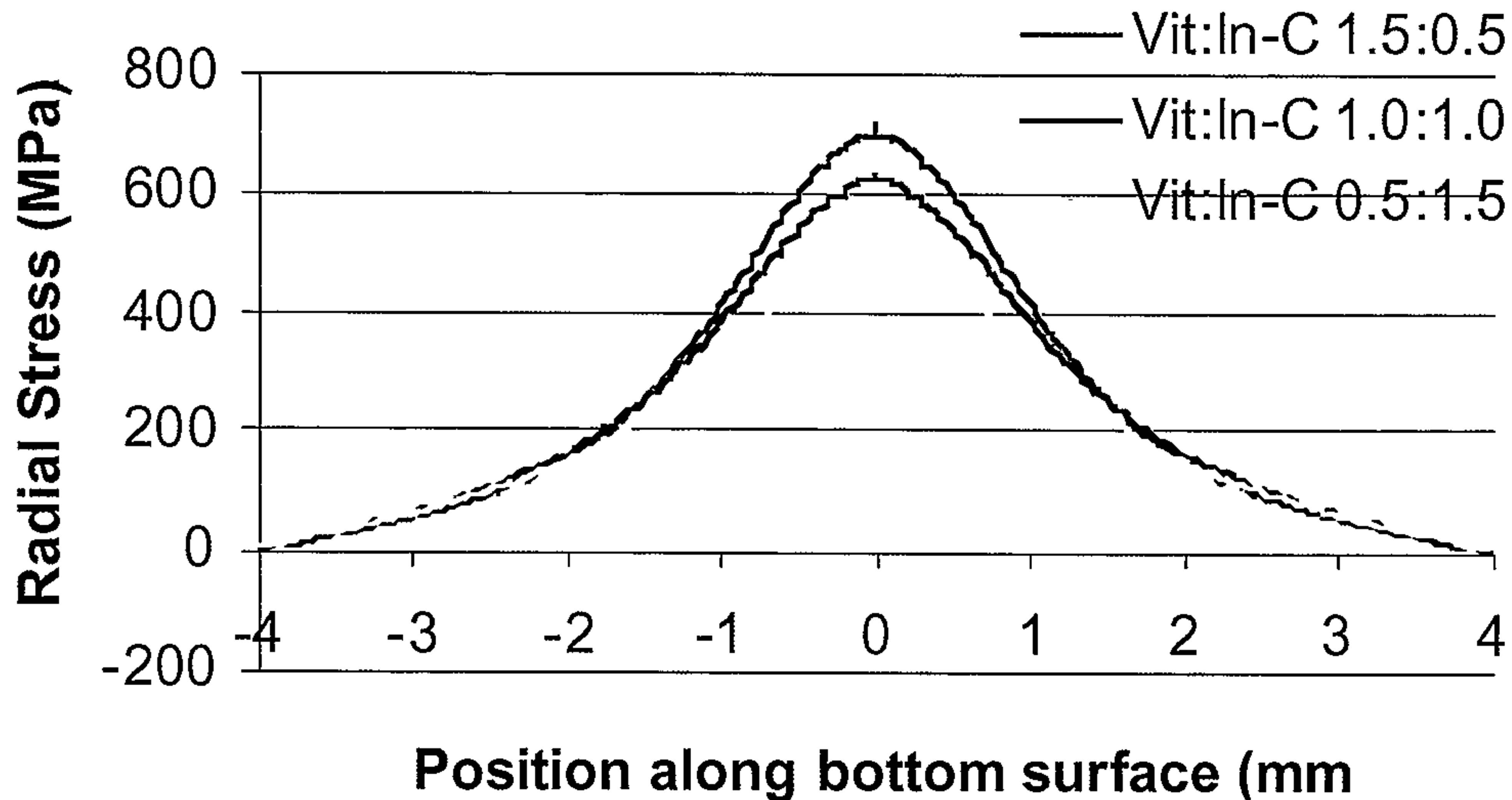


Figure 4.17. Plot of Radial Stresses for ring support model, ball loading, with varying thickness of Vitadur to In-Ceram. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc.

4.3.2. Weibull Scatter Plots and Summary

Weibull plots and moduli were also calculated for the test conditions and the relevant plots are listed below. These plots are for the punch test. The stresses calculated were based on the FEA modification of equations 4.1, 4.2 and 4.3 for the bilaminar discs.

In general the results produced Weibull moduli in the same order as the crowns tested in chapter three. The discs, being much more uniform in structure and quality gave consistently higher results as could be expected. In figure 4.18 the Weibull scatter plot for the 2 mm thick In-Ceram discs can be seen. This group of discs were not screened for porosity as described in Ironside (1995a). The scatter reveals a few results at the lower end of the curve with a more concentrated group at the top end of the curve. This could indicate the presence of a defect in the discs at the lower end of the scale and that their detection and subsequent removal from the results would improve the failure predictability. A similar and more pronounced effect can be seen in figure 4.19, where there is a high concentration of results at the top end of the curve. This would suggest that the thinner In-Ceram discs are more likely not to suffer defects, but are more severely affected when they do as the Weibull modulus is slightly less.

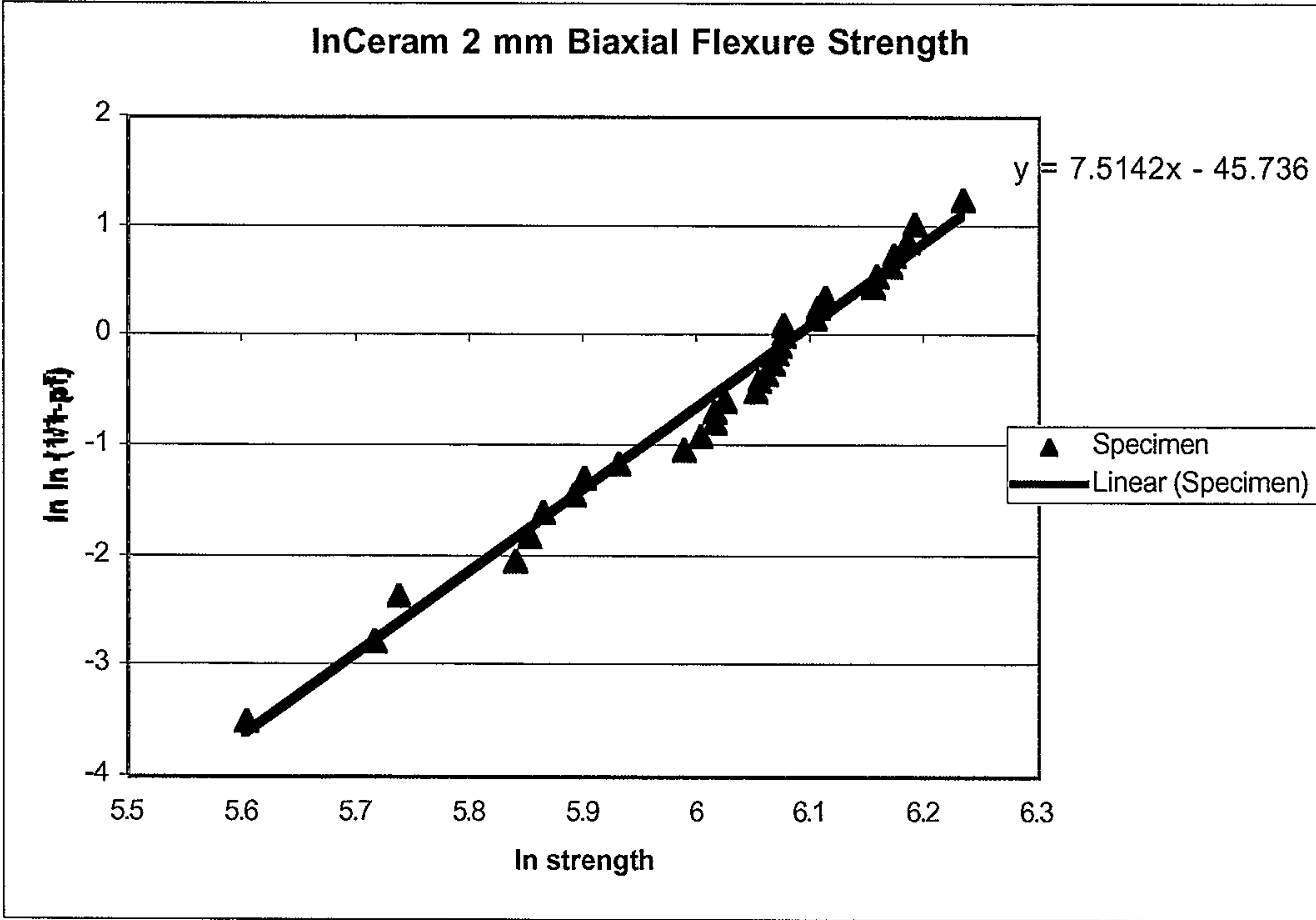


Figure 4.18 Weibull scatter plot based on the Biaxial Flexure Strength of 2 mm thick In-Ceram discs of 16 mm diameter.

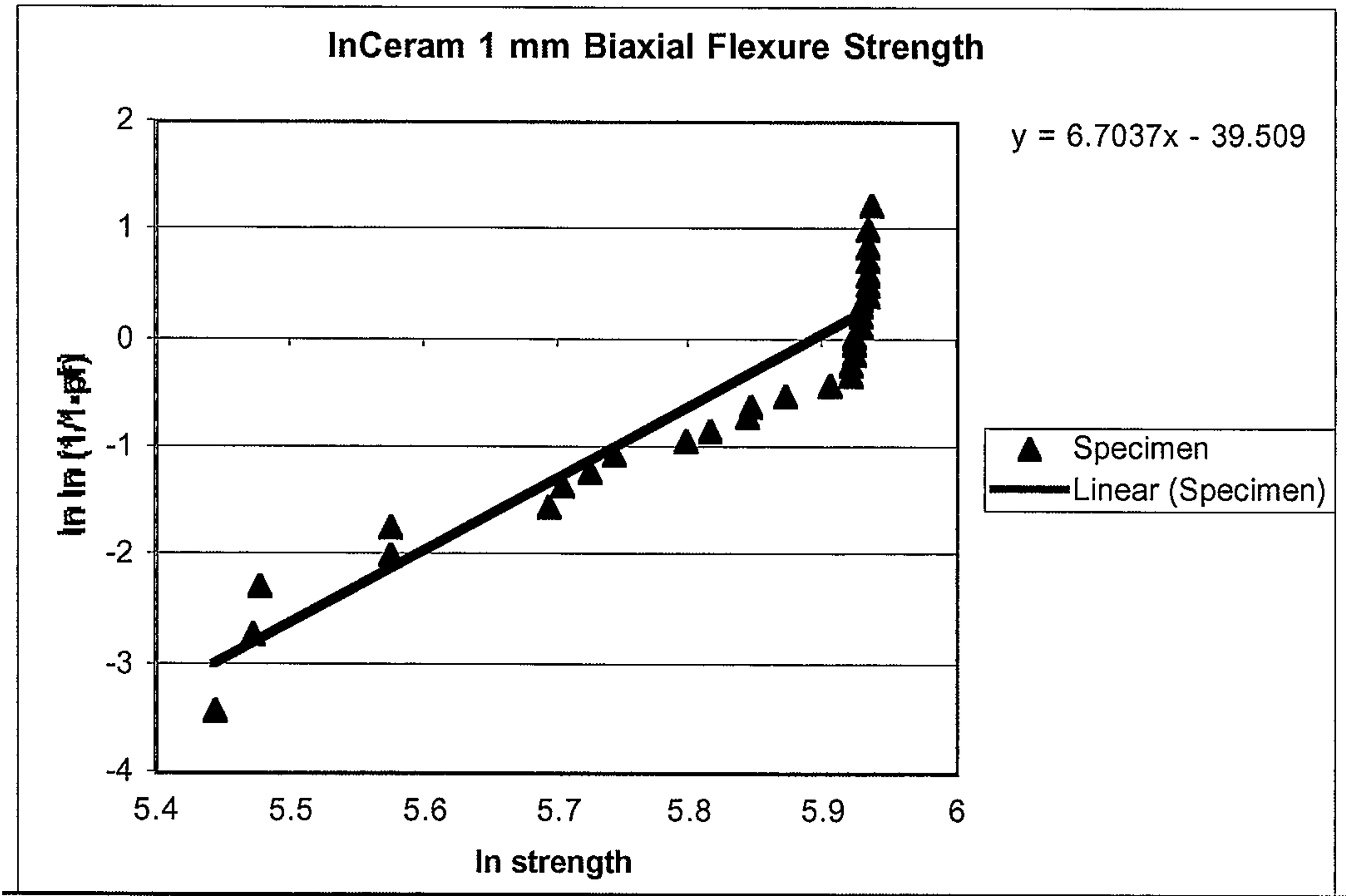


Figure 4.19 Weibull scatter plot based on the Biaxial Flexure Strength of 1 mm thick In-Ceram discs of 12 mm diameter.

The strength values for the following Weibull plots have been corrected on the basis of the FEA results. The Weibull values that result are not dissimilar to the values for In-Ceram only and possibly reflect the influence of the In-Ceram core layer on the reliability of the bilaminar construction method

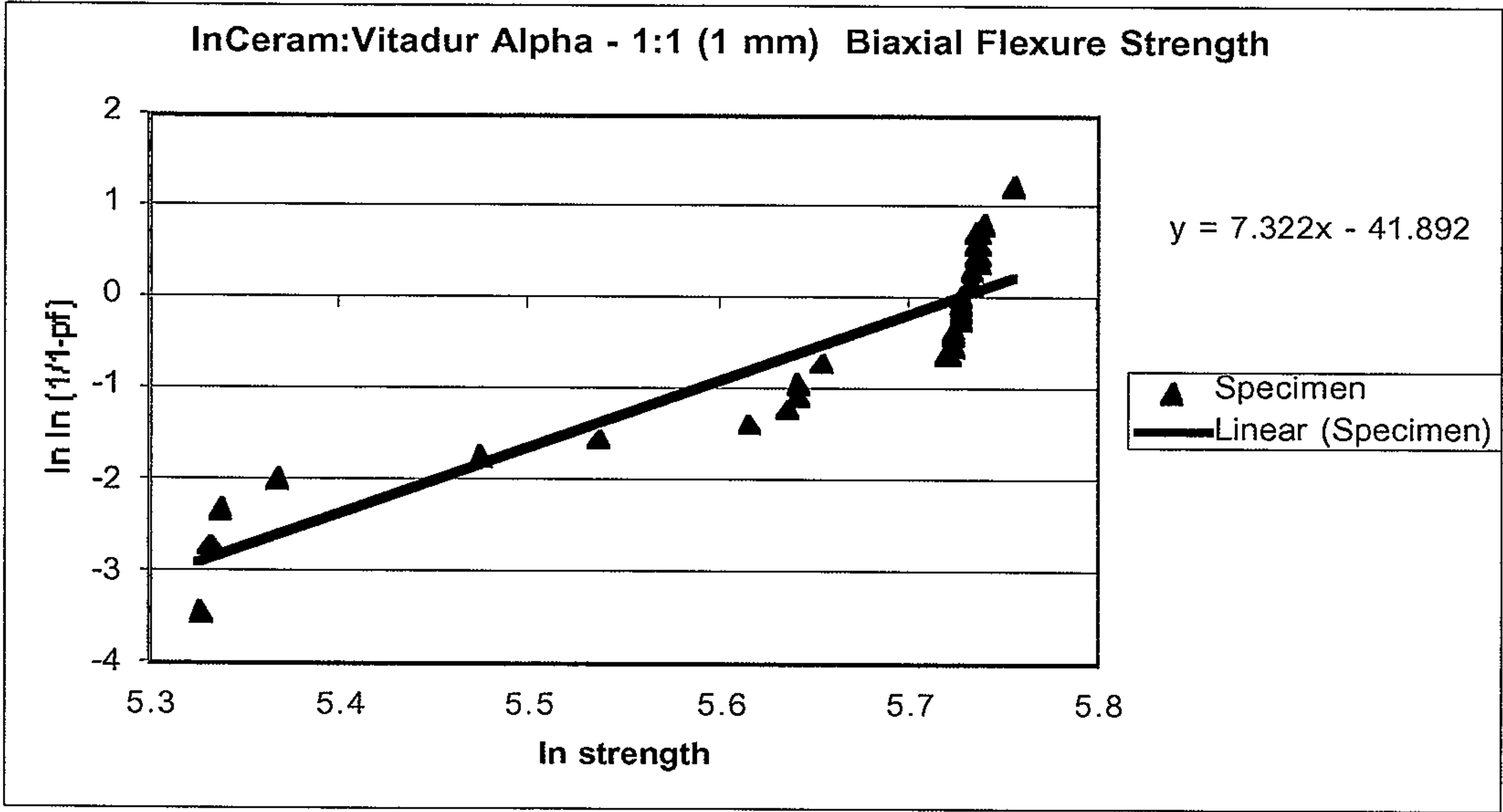


Figure 4.20 Weibull scatter plot based on the Biaxial Flexure Strength of 1 mm thick In-Ceram/Vitadur Alpha discs of 12 mm diameter. The two layers were approximately 0.5 mm thick.

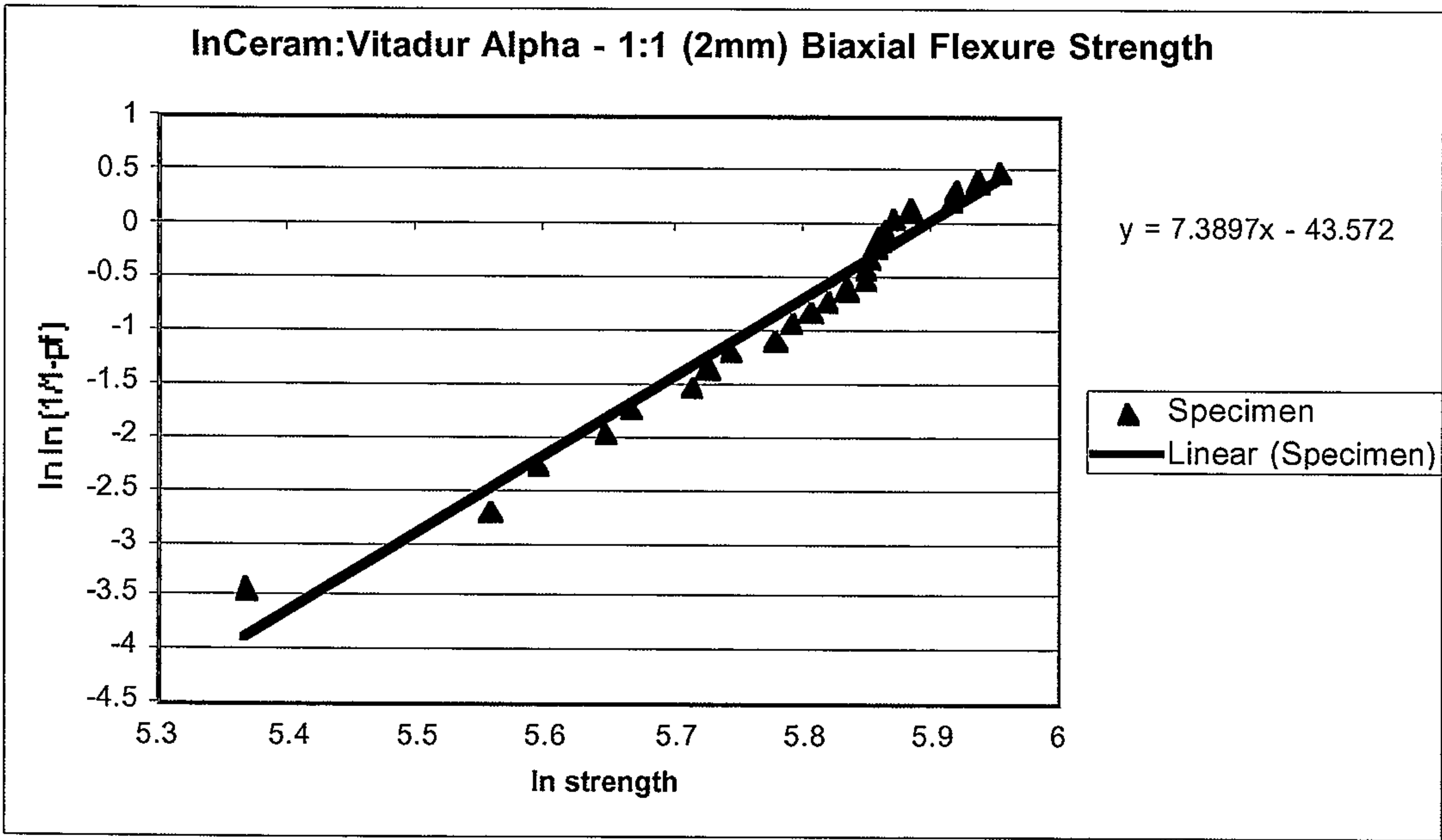


Figure 4.21 Weibull scatter plot based on the Biaxial Flexure Strength of 2 mm thick In-Ceram/Vitadur Alpha discs of 16 mm diameter. The two layers were approximately 1.0 mm thick.

Plots for the Vitadur Alpha groups are similarly plotted. The strength of the 1 mm thick discs was marginally lower than the 2 mm discs but they were more reliable according to the Weibull statistics. This may be a reflection on the construction method. It is normal practice in most commercial laboratories to build the completed shape of the crown in one build-up. The result means that there are areas where the porcelain is quite thick (> 2 mm) at times. The same technique was employed for the construction of the discs. The result being the thinner discs possibly had less noticeable porosity than the thicker discs, which would mean less internal defects and less points of residual stress concentration. The defects and stress concentrators are suspected of being causes for crown failure.

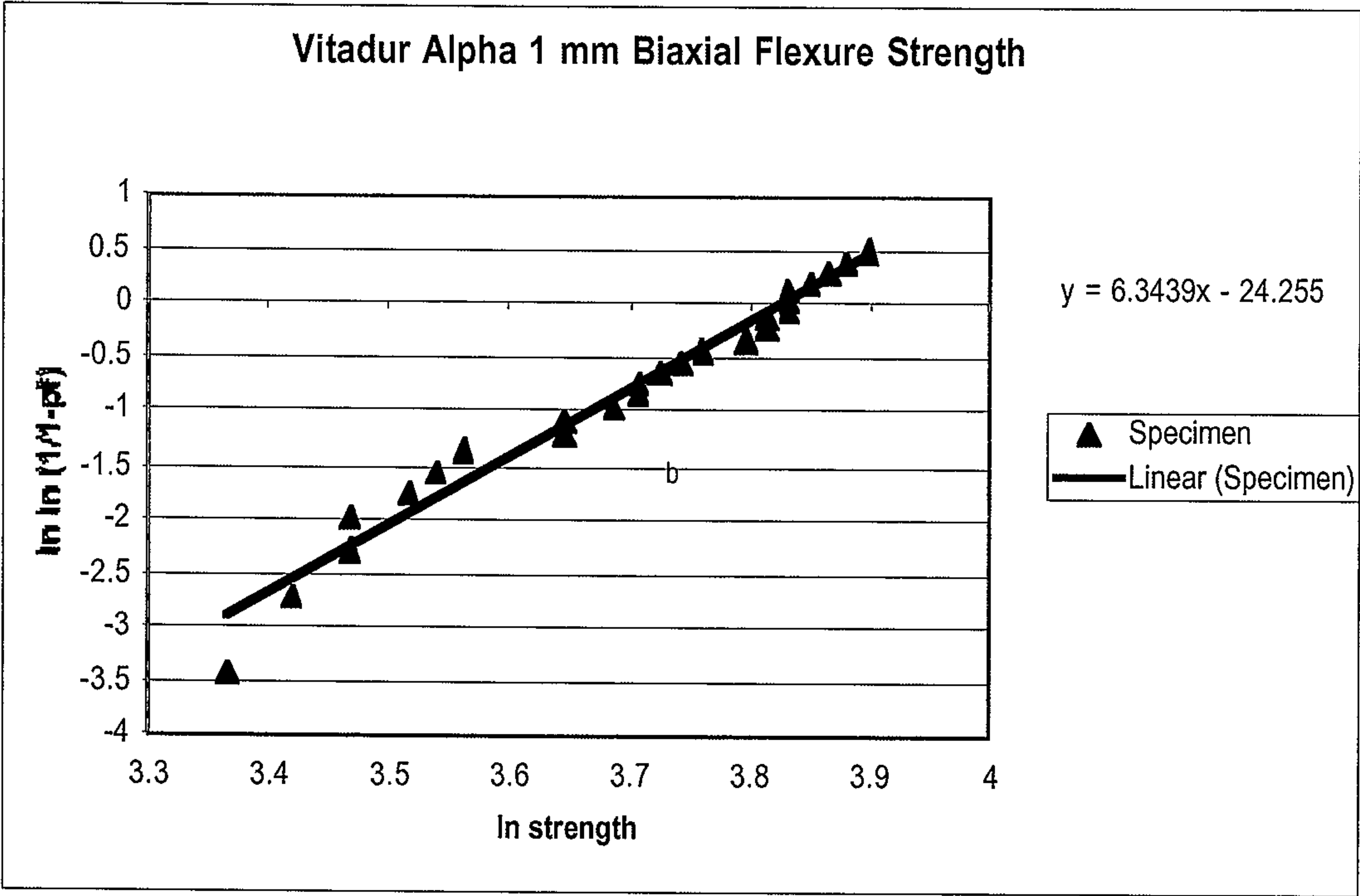


Figure 4.22 Weibull scatter plot based on the Biaxial Flexure Strength of 1 mm thick Vitadur Alpha discs of 12 mm diameter.

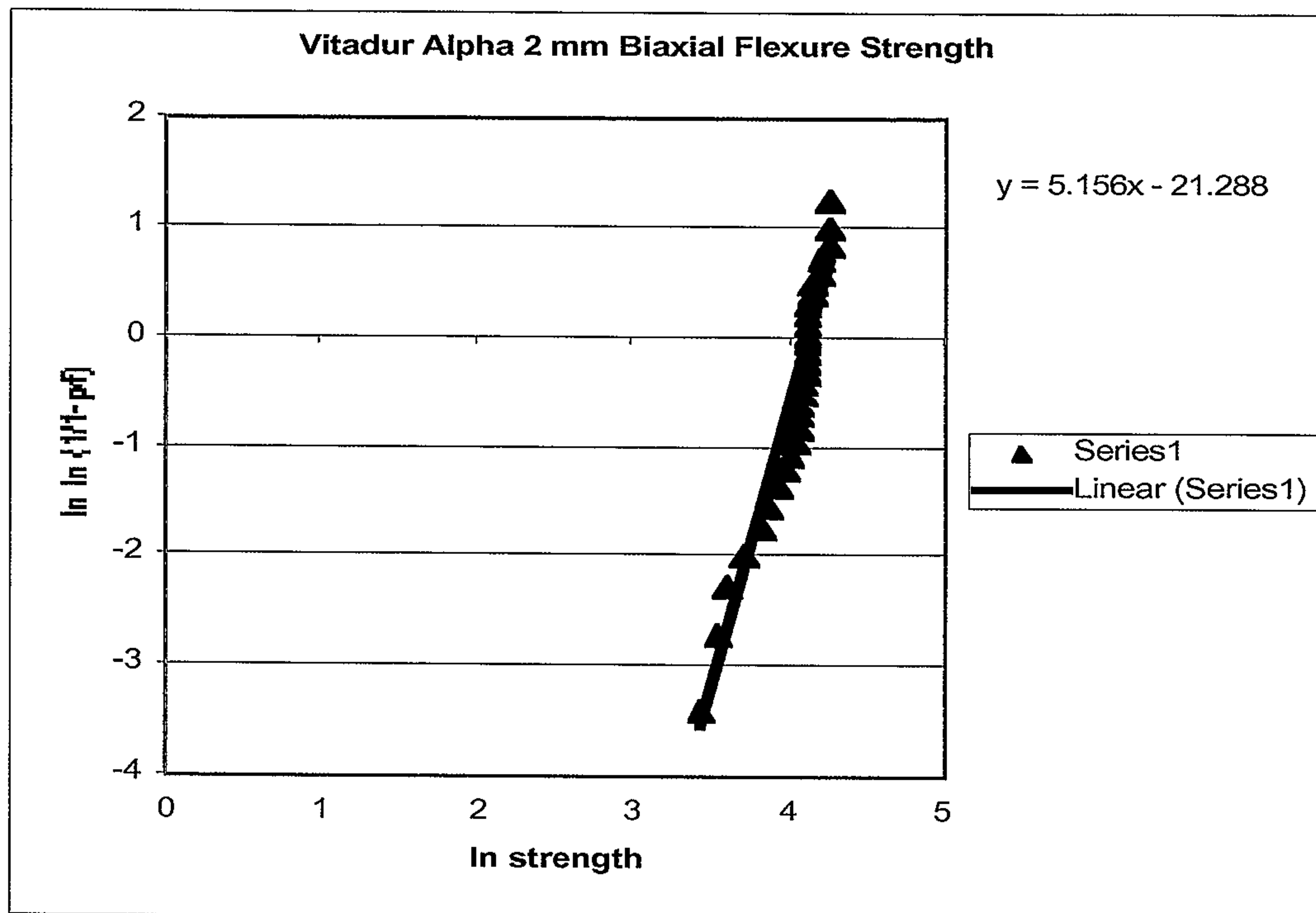


Figure 4.23 Weibull scatter plot based on the Biaxial Flexure Strength of 2 mm thick Vitadur Alpha discs of 16 mm diameter.

The data in the following Weibull plot is generated from a paper presented in 1995 at the international meeting of the International Association for Dental Research (Ironside 1995a). The paper investigated the effect of selecting In-Ceram discs on the basis of a visible increase in opacity, which was found to be an increase in porosity due to a failure of complete glass infiltration. The incidence of the porosity was found in swirls or bands and was confirmed by Scanning Electron Microscopy. The group of discs selected as being porous were tested using the biaxial technique and compared with a second group where porosity was induced by infiltrating the glass simultaneously from both sides of the disc, thus entrapping air. There was almost no difference in strength value between these two groups but they had a strength value approximately 25% lower than the group selected as porosity free. The standard deviation for the porous group was approximately double that for the non-porous group.

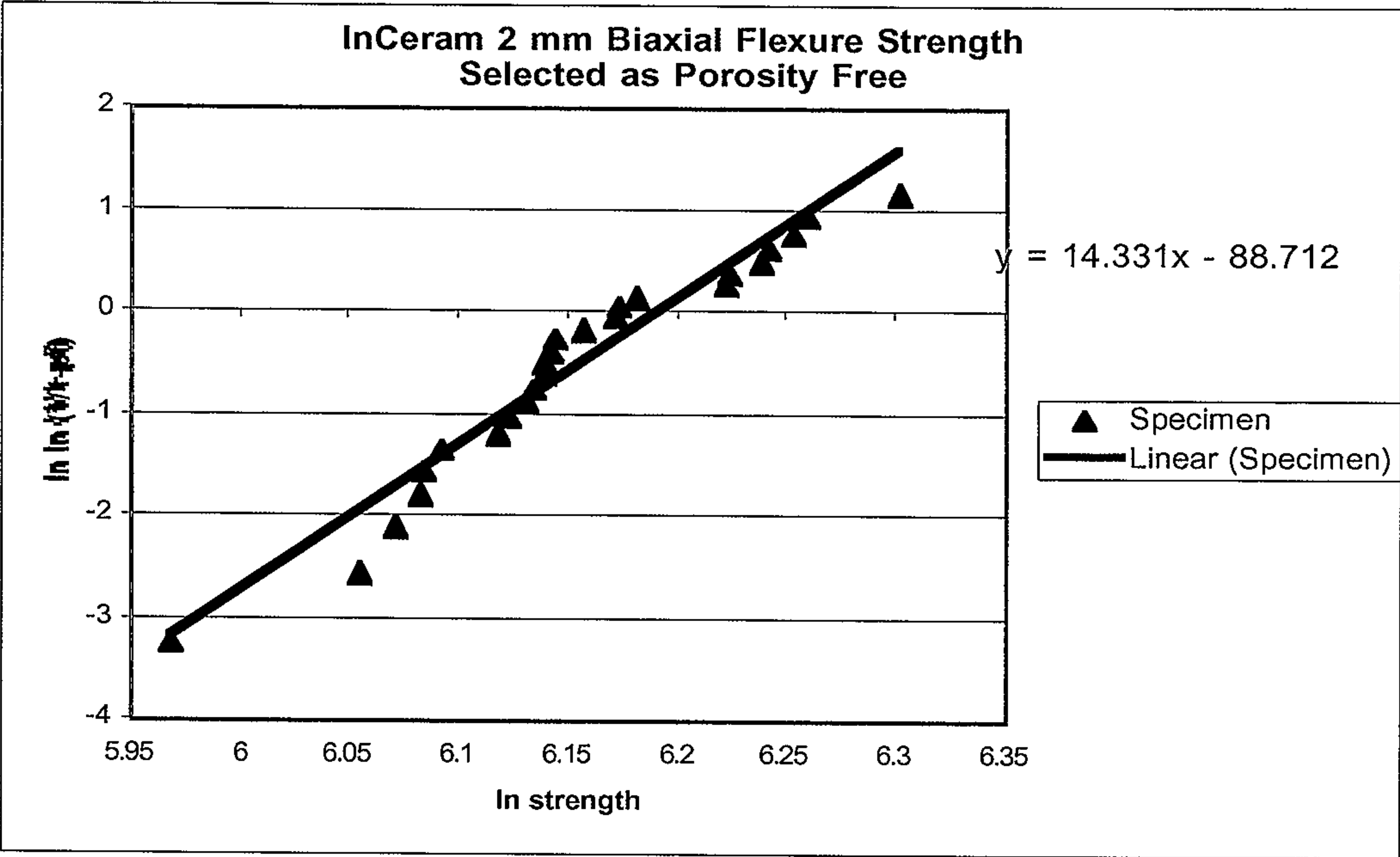


Figure 4.24 Weibull scatter plot based on the Biaxial Flexure Strength of 2 mm thick In-Ceram discs of 16 mm diameter. These discs had been visually inspected for even glass infiltration on the basis that whitish/more opaque areas contained porosity. (Ironside, 1995a).

Table 4.8 Summary of Weibull Moduli for Bi-axial Flexure Strength Tests.

Specimen Group Total Thickness mm	Weibull Modulus
In-Ceram Core (2 mm)	7.5
In-Ceram Core (1 mm)	6.7
Bilaminar (In-Ceram Core: Vitadur Alpha; 1:1) - (2 mm)	7.4
Bilaminar (In-Ceram Core: Vitadur Alpha; 1:1) - (1 mm)	7.3
Vitadur Alpha (2 mm)	5.2
Vitadur Alpha (1 mm)	6.3
In-Ceram Core (2 mm) Porosity Free	14.3

4.4 Discussion.

As indicated at the introduction of this chapter, the aims were a comparison of the strengths between disc diameters and overall thicknesses which were made to provide a degree of relevance between:

1. The range of crown sizes and thicknesses advocated by the manufacturer and seen clinically.
2. The real range of crown thicknesses that are achieved when a large group of crowns are hand made and measured under commercial laboratory conditions.
3. The disc sizes advocated for ISO 6872: 1995 (E) part 8.3.2 Biaxial Flexure Test sub section 8.3.2.2.2 Type II ceramics. There are two classes of ceramics for this type. The first, class 1, includes ceramics used for the fabrication of the support structure for crowns, veneers, inlays and onlays, which means those ceramics which are intended to be layered or veneered, e.g. In-Ceram. The second, class 2, are the veneering porcelains, e.g. Vitadur Alpha.

The preliminary evaluation of the biaxial flexure strength was based upon the erroneous assumption that the universally applied equations 4.1, 4.2 and 4.3 were independent of material properties. However the lower strength of the In-Ceram when in the bilaminar form (Table 4.4) prompted the Finite Element Analysis of this situation. It is apparent that the properties of the materials need to be taken into account as the bilaminar situation seems to temper the strain on the Vitadur Alpha and increase the tensile stress on the In-Ceram lower surface in the unsupported mode. This arises because of the different elastic moduli of the two materials and their relative deflections under this bending load. The top layer wants to bend more than the stiffer bottom layer.

Using the correction factors from the FEA the recalculated bilaminar strength was tabled in table 4.7 and provides much more consistent agreement although the strength of the thinner porcelain layer on the In-Ceram (0.5 mm on 1.5 mm) appears to be conspicuously lower than the other results. This may indicate fracture initiated from the top surface by cone crack formation as shown in chapter 3, figure 3.18.

The Weibull moduli for the discs are similar or slightly better than the result from the initial crown tests. The differences are attributable to the wider variation in the consistency of the layer thicknesses in the crowns. For the discs the standard deviation for veneer thicknesses was between 2% and 6%. The standard deviation for the crown layer thicknesses in chapter three was approximately 22% for the core layer and 31% for the veneer layer.

The significance of the crack on the top surface of the disc, as the early site of failure is important because it allows us to explore designs which prevent its occurrence by using a more supportive core layer. The argument is that the more resistant the top surface to damage, the more likely the restoration is to survive clinically. A more supportive layer in the form of the core ceramic is a direct way for improvement, rather than relying on resin bonding to tooth structure or modifying the core structure of the tooth preparation. The latter methods depend on a wide range of variables including age of the tooth, amount of core dentine remaining, or type of core replacement material such as gold, dental composite resin (wide range of types), glass ionomer or amalgam.

The results demonstrated in figures 4.11 and 4.15 would indicate that a thicker core layer would increase the load required to start the radial or tensile cracks seen on the underside. Significantly we can also see that the overall support for the bilaminar system will influence the onset of a crack or not. The In-Ceram discs by themselves produced both higher loads for fracture and better Weibull moduli values than either corresponding thickness of the bilaminar systems and the Vitadur Alpha on its own.

From table 4.7 it has been shown that the flexural strength of In-Ceram is approximately 530 MPa and the flexural strength of Vitadur Alpha is approximately 84 MPa.

The Weibull moduli of the bilaminates are notably higher than for the Vitadur Alpha specimens, indicating the In-Ceram bottom layer has improved the reliability of the overall systems, which is in keeping with the FEA results that suggest that the Young's Modulus for the In-Ceram has improved the strength of the bilaminate.

4.5 Conclusions.

The significance of the difference between the Weibull moduli of the discs tested and the initial crown tests indicates further investigation of the effect of layer thicknesses and support is required and that deliberate design strategies for the layers might improve the fracture resistance.

The support layer beneath the In-Ceram influences the origin of the crack, with stiff support appearing to result in very low tensile stresses on the under surface. The use of Finite Element Analysis will be employed in the following chapter to quantify the levels of tension in this surface under different support conditions.

Contact Fracture of Supported Discs

5.1 Introduction

In the previous chapter it was shown how the influence of bilaminar thickness ratio affected the strength and critical load to fracture of the discs under flexure. It was shown that an increase in core thickness at the expense of veneer thickness improved the load before fracture occurred. This concept is limited because a critical requirement for the clinical use of these crowns is that they are the same aesthetically as natural teeth. The main drawback with the use of glass infiltrated alumina is the reflective interface at the junction between the feldspathic veneering porcelain and the alumina based core. If the ceramic core is too close to the surface, the crown no longer looks natural. The only practical areas where the ceramic can be very near the surface are the palatal surfaces of the upper anterior teeth and the disto-occlusal aspects of the upper molars.

In this chapter the discs will be tested where they are fully supported by a steel base. This approach provides the other end of the spectrum for support. The metal gives an indication of the stresses directly below the contact when that part of the ceramic restoration is supported by a hard metal core, e.g. a hard Type III or IV gold alloy or even base metal alloys such as cobalt-chrome alloy.

Previously the 1.6 mm diameter flat steel punch and the 5 mm diameter steel ball, were applied vertically downwards at the centre of the disc, producing stresses that were the result from the overall pressure. There are compressive stresses directly beneath the punch on the top surface of the disc and tensile stresses both on the undersurface and just outside the periphery of the punch contact area. In this chapter the 5 mm diameter steel ball indenter only is used on the supported discs because it is felt that it is more representative of the clinical situation. The loads to fracture produced by the steel punch were excessively high and such a scenario is not often found clinically.

5.2 Materials and Methods.

Monolithic and bilaminar discs 16 mm in diameter and 2 mm thick were constructed using combinations of the glass infiltrated alumina core material, In-Ceram®, and the

veneering porcelain, Vitadur Alpha®. Table 5.1, which lists these combinations, appears below. The construction method was the same as the routine described in chapter four.

Table 5.1 Variations of the different ceramic ratios in the bilaminar discs.

Group No.	Core Porcelain Thickness: mm	Veneer Porcelain Thickness: mm
1	2.0	0.0
2	1.5	0.5
3	1.0	1.0
4	0.5	1.5
5	0.0	2.0
6	1.0	0.25
7	1.0	0.5
8	1.0	0.75

Groups 1 to 8 were tested mechanically with the ball indenter. The disc models for groups 1 to 5 were also tested using a proprietary Finite Element Analysis program, "Strand 7", (G+D Computing, 1999). In addition an analytical program, "Elastica", (Chudoba et al., 2000a and b), for stress analysis of the area about and below the indenter contact was used for groups 2, 3, 4, 6, 7 and 8. The difference between the two programs is that the Elastica program can provide highly detailed contact stresses at the surface without the need for extremely fine FEA mesh construction and the large computing calculations associated with it. The nature of the stress gradients for a spherical indenter are such that there is a very sharp gradient in the region of the contact circle radius, where the stresses suddenly change from compressive to tensile. This is where the FEA analysis requires extremely fine mesh. The FEA system does present a better overall view of the stresses within the body of the specimen, enabling a view of the stresses on the undersurface and support systems to be seen.

5.2.1. Mechanical Testing

A series of the 16 mm diameter discs was subjected to testing using a 5 mm hard steel spherical indenter. Construction of the discs was the same as described in chapter 4. In this case a flat steel base supported the discs. This was to provide a picture at the extreme opposite end of the support spectrum where the ceramic has relatively high support against bending. A slightly lesser scenario clinically is where a hard gold core would

support the crown. The experimental arrangement with the flat support and the 5 mm diameter ball indenter with the same guiding supports are depicted below in figure 5.1.

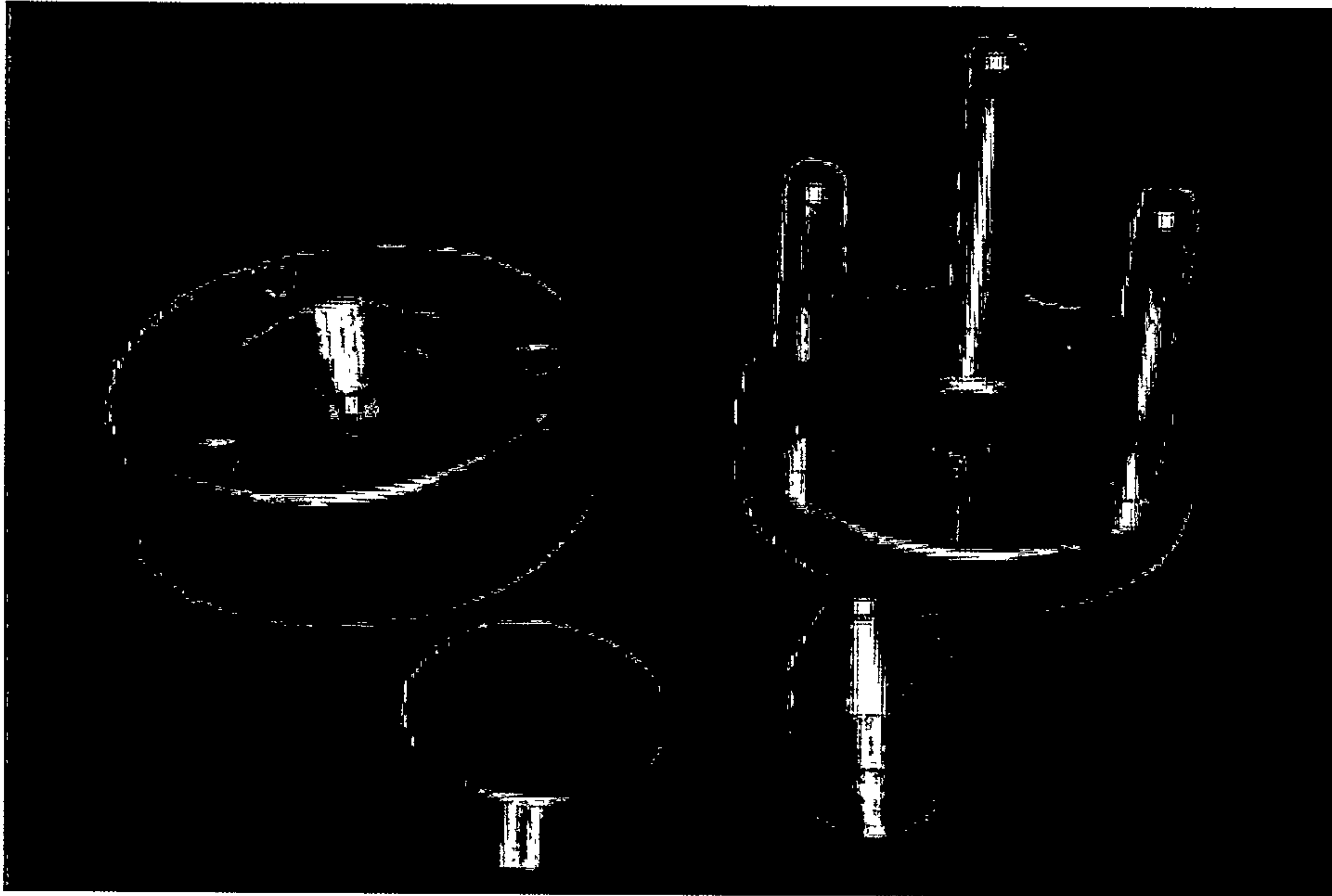


Figure 5.1 The components of the flexural test rig. The lower brass base for the guiding rods and the flat steel base are on the left and the 5 mm hard steel ball and the upper brass base with the guide rods is on the right.

Mechanical testing on the flat steel base for the monolithic In-Ceram and those bilaminar discs with a majority thickness of In-Ceram could only be described as explosive. Invariably the disc was shattered into many pieces and a guard was necessary around the test rig to prevent injury. The biaxial tests by contrast usually produced only three or four pieces.

5.2.2. Finite Element Analysis

For the supported scenario, the properties of the support systems need to be taken into account when using Finite Element Analysis. The properties are listed in table 5.2. The support systems are loaded by the disc as it is pressed by the indenter which causes an opposing reaction. The opposition to the force will result in a build up of stress at the interface between support and disc. The stress magnitude will be influenced by the deflection of the disc into the support. The stiffer the support, the less deflection available to the disc. Presumably this will result in less tensile stress on the bottom surface of the disc and more compressive stress in the disc as loading by the indenter continues. The Finite Element Analysis should therefore show higher compressive loads on top of the

discs and lower tensile stresses on the bottom as the Young’s modulus for the support increases.

Table 5.2. Properties of material used for FEA.

Material	Young’s Elastic Modulus (GPa)	Poisson’s ratio
Vitadur Alpha	70	0.28
In-Ceram Alumina	287	0.22
Steel	210	0.33
Dentine	20	0.23

5.2.2.1 Dentine Support below Flat Ceramic Disc: Flat Punch Load

Again five different axisymmetric models were made of the disc. Each model had a radius of 8 mm, and a thickness of 2 mm. Each model was varied by changing the ratio of Vitadur Alpha to In-Ceram Alumina. Axisymmetric Finite Element Analysis (FEA) used axisymmetric 2D elements. For each model, 1600 of these 2D elements were used. The different thickness combinations used for the five models were 2.0:0.0; 1.5:0.5; 1.0:1.0; 0.5:1.5; 0.0:2.0.

Below each model was constructed a base made of dentine. This was done using axisymmetric 2D elements. The radius of the dentine base was 16 mm and it had a height of 10 mm. Around the outside edge of the dentine and base of the dentine, constraints were applied that allowed no turning moment or translation movement. Figure 5.2 is a diagram of the FEA mesh and loading conditions.

All models had the same vertical loading, directed downwards. The loading was an edge pressure of 746 N/ mm² applied to the top edge of 8 elements. This simulated a flat punch load of 1500 N of radius 0.8 mm. This situation enabled a comparison with punch loading induced flexure for the three ball supported discs as presented in the previous chapter.

The material properties were the same as those for the ring support system.

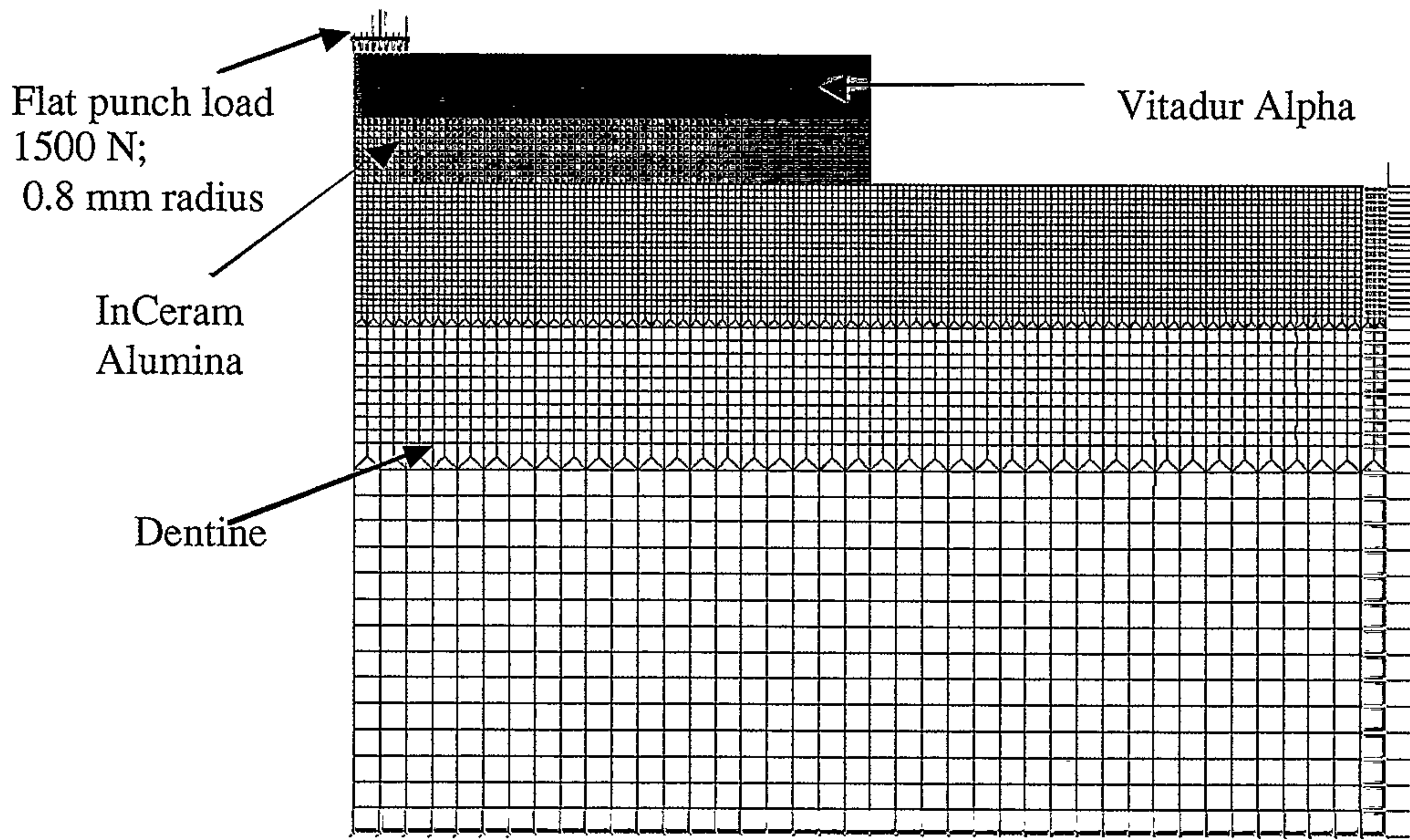


Figure 5.2 Axisymmetric 2D element model of biaxial disc for punch loading on dentine support. Ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

5.2.2.2 Dentine Support below Flat Ceramic Disc: 5 mm Ball Load

This model is the same as that used for the Punch loading, dentine base. However the loading applied is a ball loading – described in the section above. Figure 5.3 is a diagram of the FEA mesh and loading conditions.

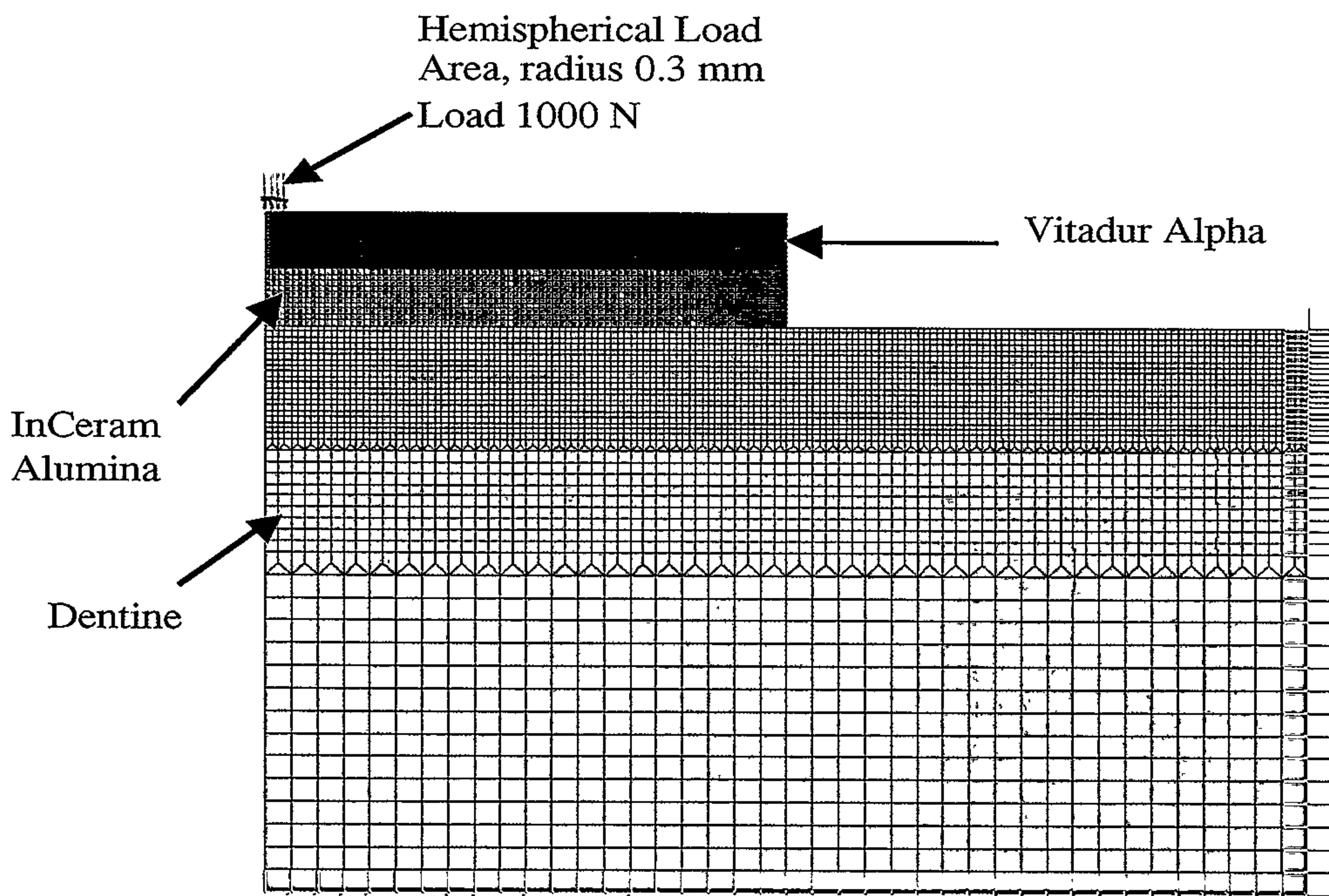


Figure 5.3. Axisymmetric 2D element model of biaxial disc for ball loading on dentine support. Ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

5.2.2.3 Steel Support below Flat Ceramic Disc: 5 mm Ball Load

Again the same models as those for the dentine base were used. However, the element properties of the base were defined as that of steel. The configuration can be seen in Figure 5.4. The material properties of steel are defined in Table 5.4.

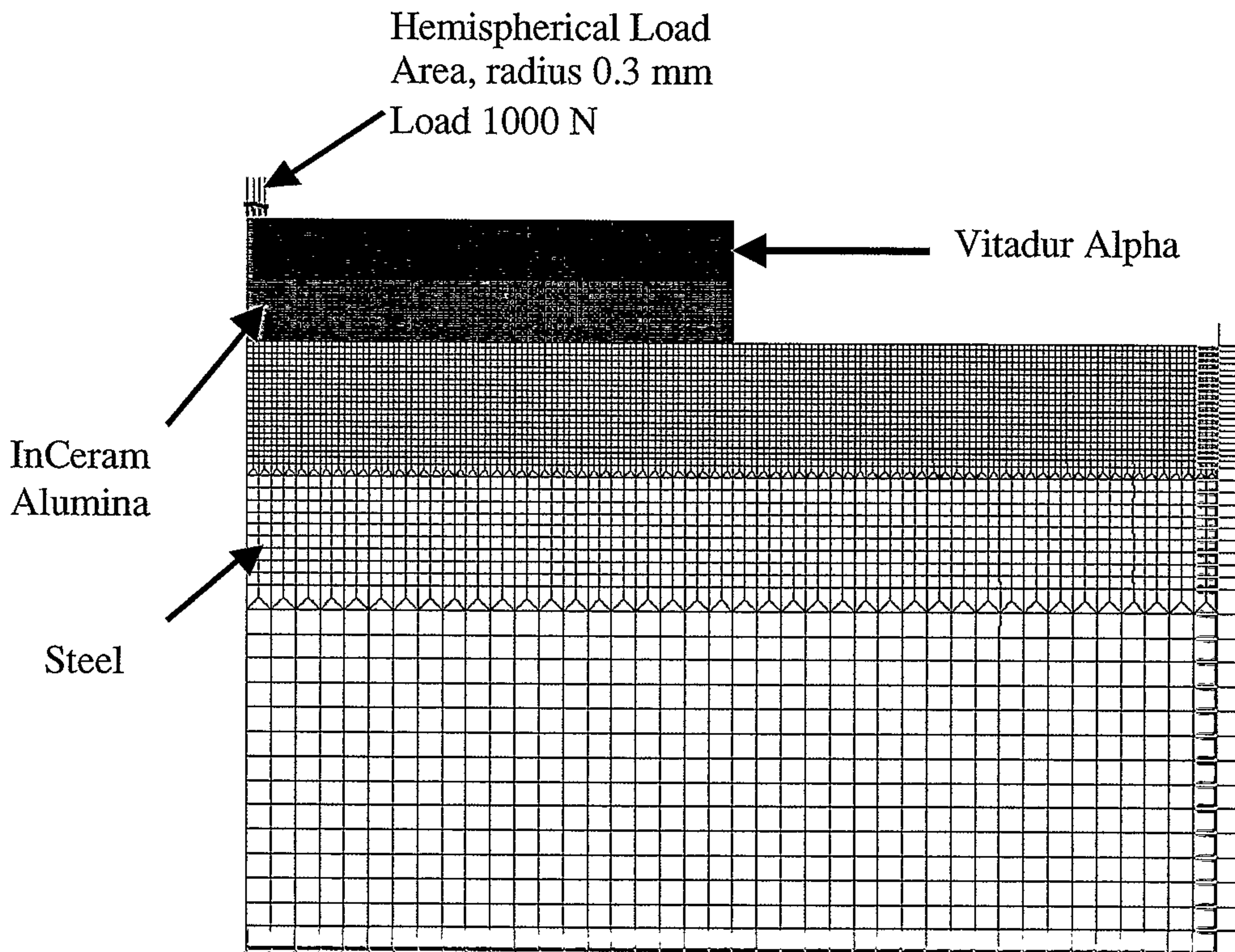


Figure 5.4 Axisymmetric 2D element model of biaxial disc for ball loading, on steel support. Ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

5.2.3 Analytical Modelling of Mechanical Contacts

The loading of the supported and unsupported discs develops contact stresses about the ball or punch loading site. As shown in the chapter 3, Hertzian cone cracking appeared to be an integral part of the failure mechanism. In this section the magnitude of the contact dimension and stresses are estimated from the Hertzian contact mechanics. A more detailed analysis using a specific analytical program called "Elastica" was discussed in section 2.9.3 of Chapter 2.

Part of the process for determining the stresses developed is to know the contact area beneath the spherical indenter. The radius of the circle of contact a is given by equation (5.1) below:

$$a^3 = \frac{4}{3} \frac{kPR}{E} \quad (5.1)$$

Equation 5.1 was discussed earlier in chapter 2 in section 2.3.1.2. P is the indenter load, R is the indenter radius, E is the Young's Modulus for the specimen and k is an elastic mismatch factor given by equation (5.2) below:

$$k = \frac{9}{16} \left[(1 - \nu^2) + \frac{E}{E'} (1 - \nu'^2) \right] \quad (5.2)$$

Here, ν is the Poisson's ratio of the specimen and ν' and E' are the Poisson's ratio and Young's Modulus respectively for the Indenter.

Hertz also found that the maximum tensile stress in the specimen occurs at the edge of the contact circle (Fischer-Cripps 1998) on the specimen surface and is given by equation (5.3):

$$\sigma_{\max} = (1 - 2\nu) \frac{P}{2\pi a^2} \quad (5.3)$$

This is the stress that is considered as being responsible for the production of Hertzian cone cracks. It acts in a radial direction on the surface outside the indenter and decreases as the inverse square of the distance away from the centre of contact. By combining equations 5.1 and 5.3 the maximum tensile stress outside the indenter can be expressed in terms of the indenter radius R :

$$\sigma_{\max} = \left(\frac{(1 - 2\nu)P}{2\pi} \right) \left(\frac{3E}{4k} \right)^{2/3} P^{1/3} R^{-2/3} \quad (5.4)$$

5.3 Results –Supported Discs.

The results from the mechanical testing, finite element analysis, and analytical stress calculations are presented below. The finite element analysis gives an indication of the stresses developing three dimensionally throughout the specimens and the analytical solutions using "Elastica" provide quantitative information about the peak stresses and their distributions, particularly on the surface and directly below the indenter.

5.3.1 Results from the Mechanical Testing.

Table 5.3 In vitro contact radii, failure loads and Principal stress values for In-Ceram/Vitadur Alpha discs according to changes in thickness ratios and using compression from a 5 mm steel ball against the specimen on a flat steel base. See table 5.1 for the thickness and layer ratios for each group.

Group No.	Contact Radius (µm)	Average Failure Load: Newtons	Principal Tensile Stress: S1 (MPa)
1	356	2825	1775
2	402	2213	1267
3	366	1589	974
4	321	1046	724
5	292	736	638
6	265	681.6	861
7	285	845.8	841
8	333	1188	824

The principal stresses were calculated using the Elastica program.

5.3.2 Results from the Finite Element Analysis.

The Finite Element Analysis results for the three systems tested are shown below. In each case the stress distribution along the axis and also in the In-Ceram at the In-Ceram support interface for the bilaminar disc is shown. The system loaded by the flat punch had a broader load distribution than the 5 mm ball loaded systems and the dentine support demonstrated increased tensile stress on the lower surface of the In-Ceram.

5.3.2.1 Dentine Support below Ceramic Disc: Flat Punch Load

The peak compressive stresses for the conditions in figure 5.5 were 368 MPa on the top surface of the Vitadur Alpha layer and the peak tensile stress on the bottom surface of the In-Ceram was 604 MPa. Figure 5.6 demonstrates a build-up of stress at the interface which could be described as mildly compressive. The magnitude of the stress for the punch scales linearly with the load.

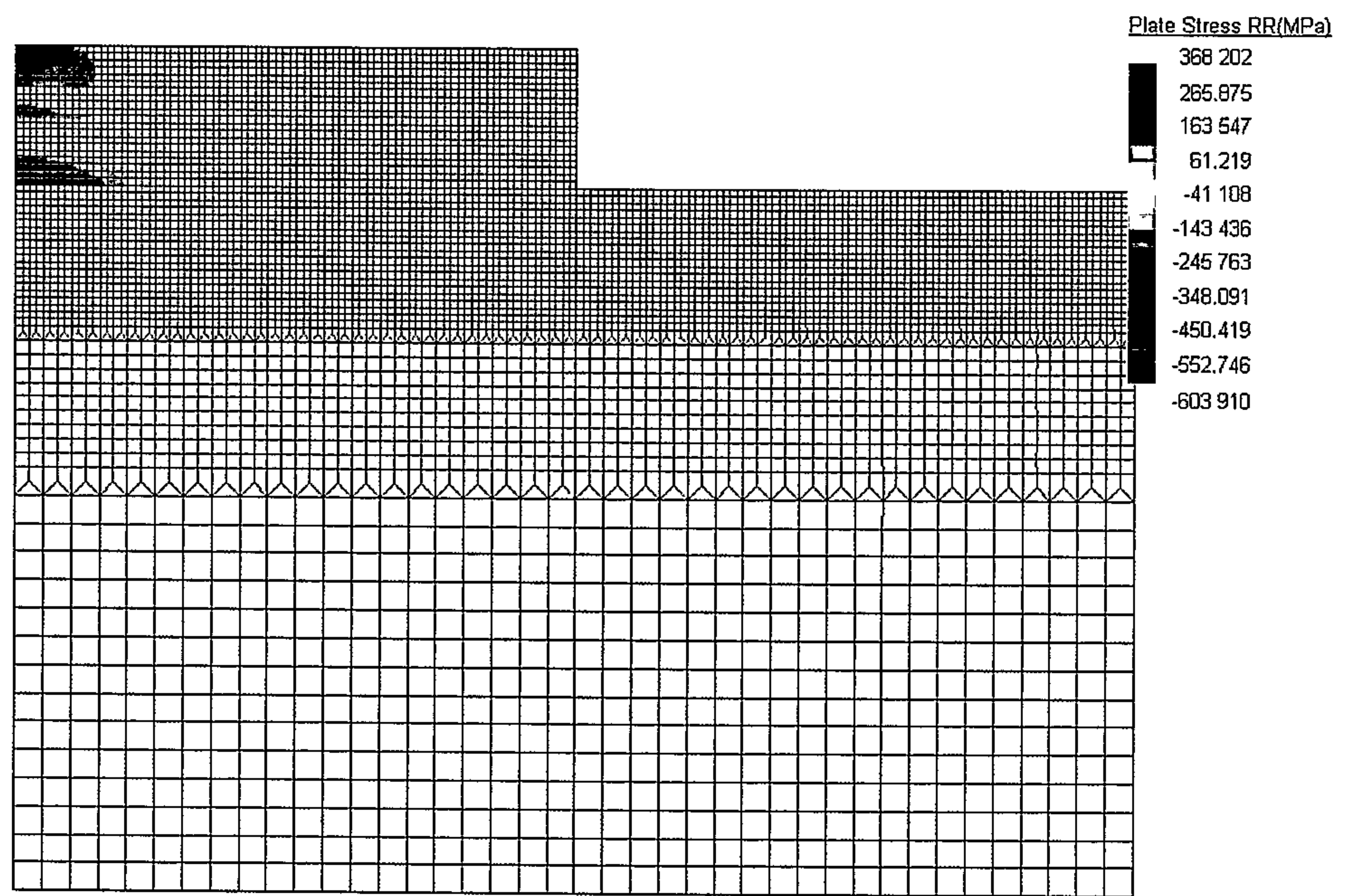


Figure 5.5. Radial Stress (MPa) of disc model, punch loading, on dentine base for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. (P = 1500N)

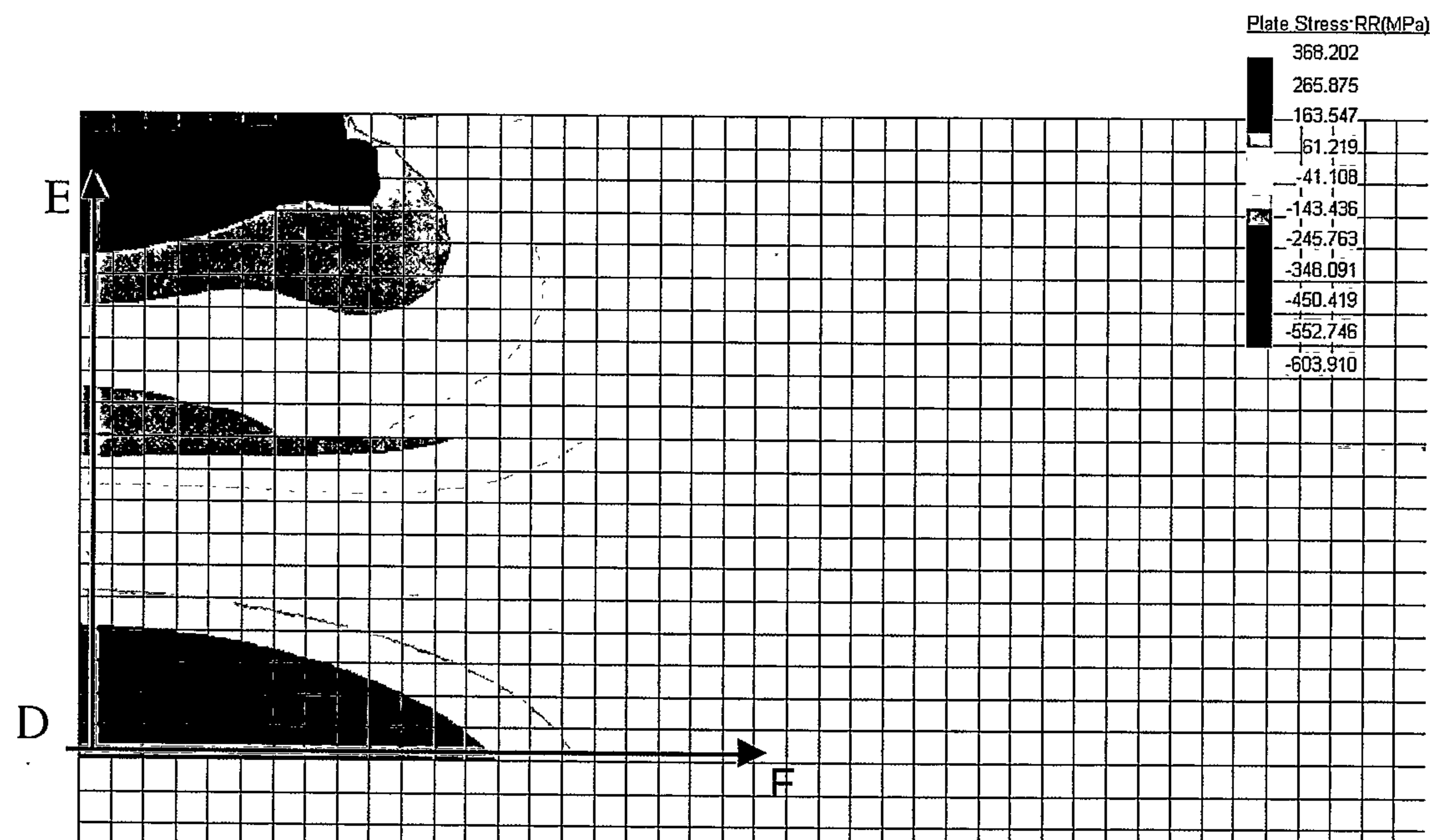


Figure 5.6. Radial Stress (MPa) of disc model centre region for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. Disc on dentine base with punch loading.

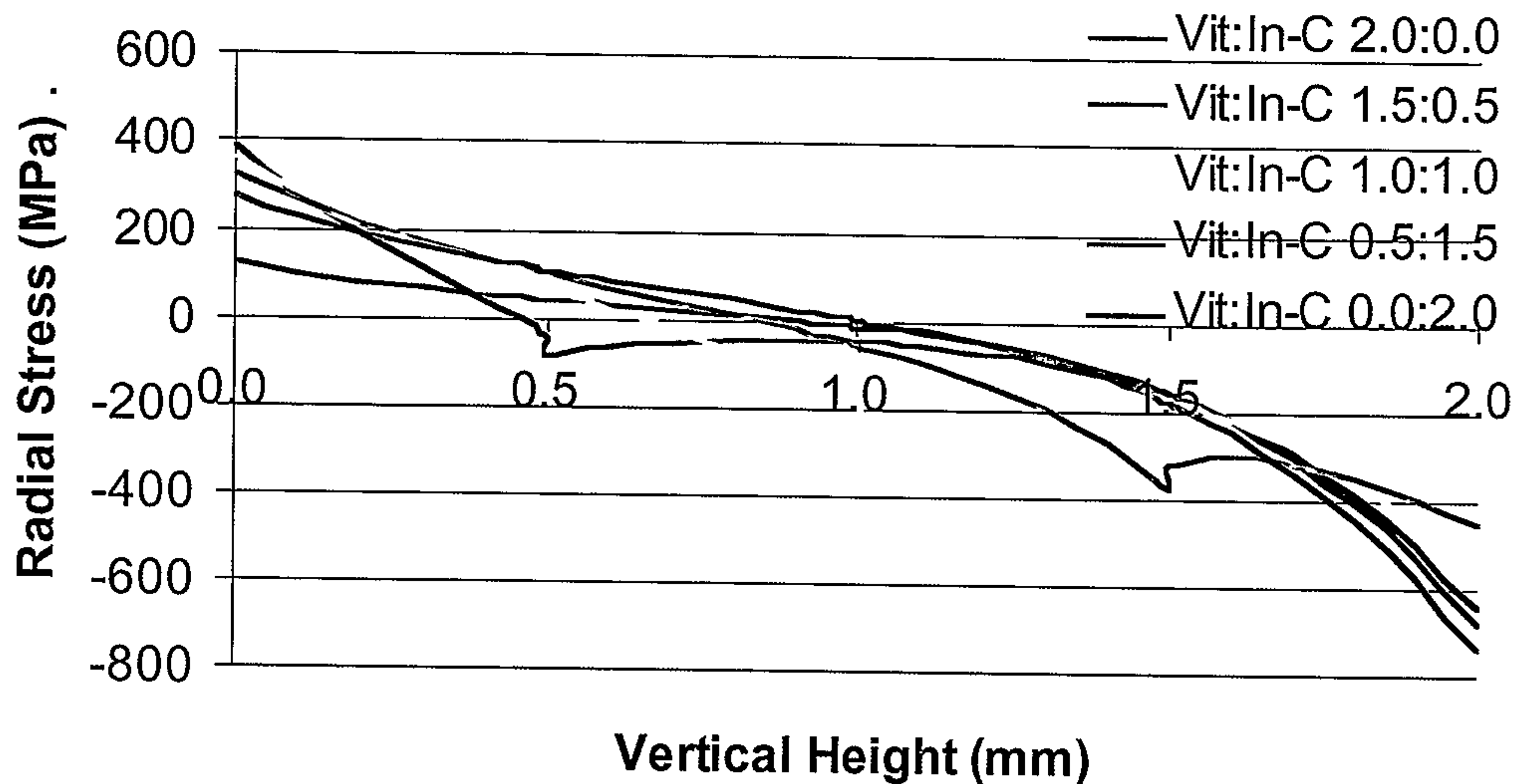


Figure 5.7. Plot of Radial Stresses for each model, dentine base, punch loading. Stresses measured along the axis of symmetry from point D to point E.

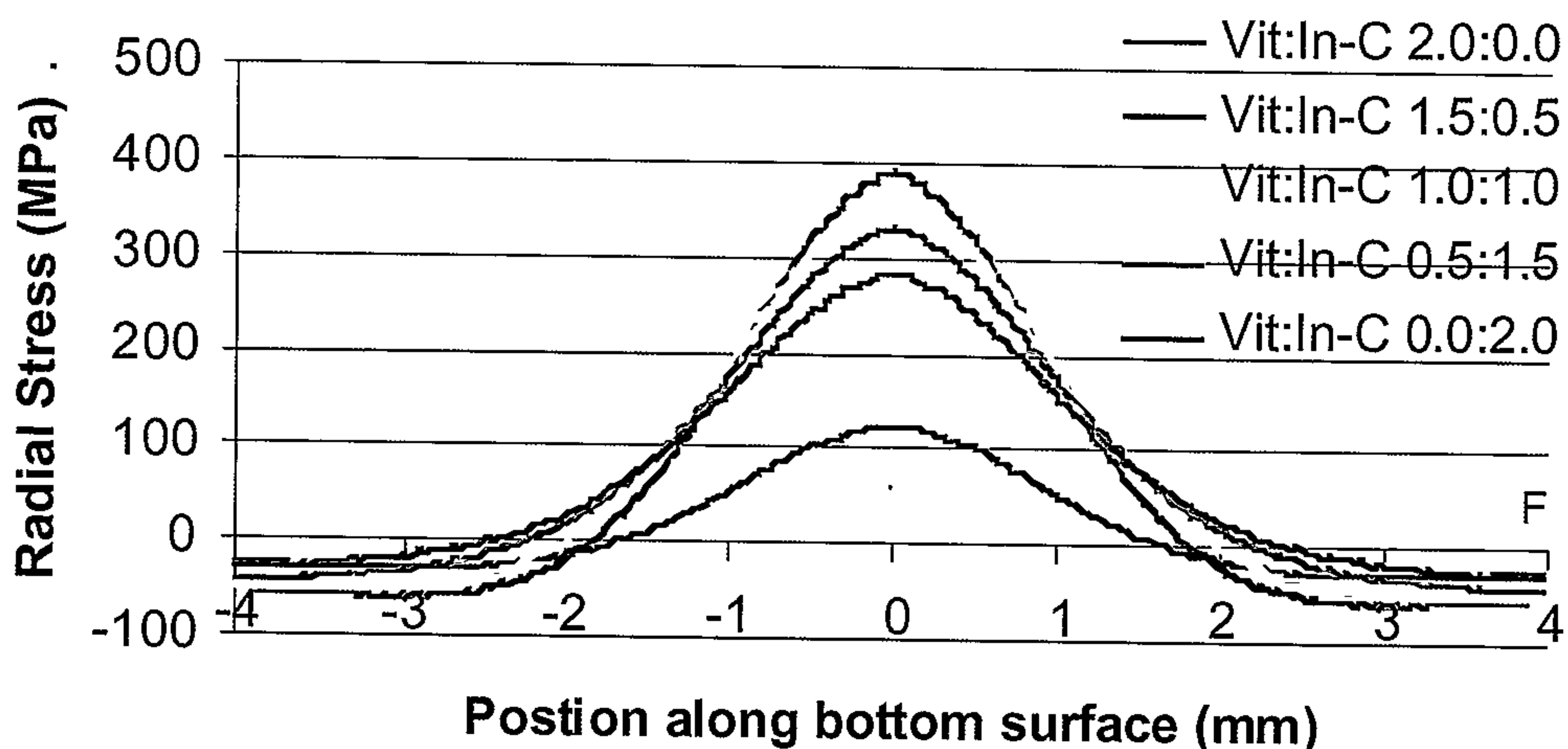


Figure 5.8. Plot of Radial Stresses for each model, dentine base, punch loading. Stresses measured along the bottom of surface from point D to point F

Figures 5.7 and 5.8 demonstrate the effect of a monolithic layer and its radial stress distribution compared with the bilaminar condition. Whereas the monolithic Vitadur Alpha has the lowest flexural stress (when all are loaded to 1500 N), the combination of the two layers in this situation still produces the highest tensile stress levels at the centre of the bottom surface. The Vitadur Alpha also has the lowest tensile stress on the bottom surface at fracture, followed by the 2 mm thick In-Ceram disc. However the load supported by the In-Ceram is approximately 4 times that of the Vitadur Alpha, whereas the ratio of the

flexural strengths (table 4.7) is almost 10 times. The ratio of the stresses at the ceramic dentine interface are given in table 5.4 below and clearly show the influence of the low modulus dentine supporting the low modulus and more potentially deflecting Vitadur Alpha than the higher modulus In-Ceram. It is also evident that the bilaminar discs generate higher stresses within the In-Ceram at the interface.

Table 5.4 Ratio of maximum tensile radial stress for each disc ratio to the maximum tensile radial stress for Vitadur Alpha to In-Ceram Alumina 0.0:2.0.

Case	Ratio of Vitadur Alpha to In-Ceram Alumina	Maximum tensile radial stress in disc (MPa)	Ratio of Case 10 to the other cases
6	2.0:0.0	125.1	0.44
7	1.5:0.5	389.1	1.38
8	1.0:1.0	368.2	1.30
9	0.5:1.5	328.9	1.16
10	0.0:2.0	282.7	1.00

5.3.2.2 Dentine Support below Biaxial Disc 5 mm Ball Load

The 5 mm diameter steel ball loading of the disc produces a very different result to the flat punch. As would be expected, the contact area is much less, but varies according to the actual load. The calculated radius, using equations 2.17 and 2.18 is approximately 0.3 mm, which concentrates the compressive stresses into a much smaller area and increases the pressure on the porcelain veneer. The low elastic modulus of the dentine allows sufficient flexure of the bilaminar disc to create large tensile stresses on the bottom surface. For the conditions in figures 5.9 and 5.10 the maximum compressive stress on the top surface is 3.795 GPa and the tensile stress on the bottom surface is 381 MPa. These conditions are more likely to allow the formation of the cone crack on the top surface prior to the formation of the radial crack on the bottom surface.

Figure 5.10 also demonstrates the beginnings of stresses across the interfacial layer. This is because the materials have both different elastic moduli and Poisson’s ratios creating different ranges of movement in their component parts. This not only creates stresses within each material but also across the interface.

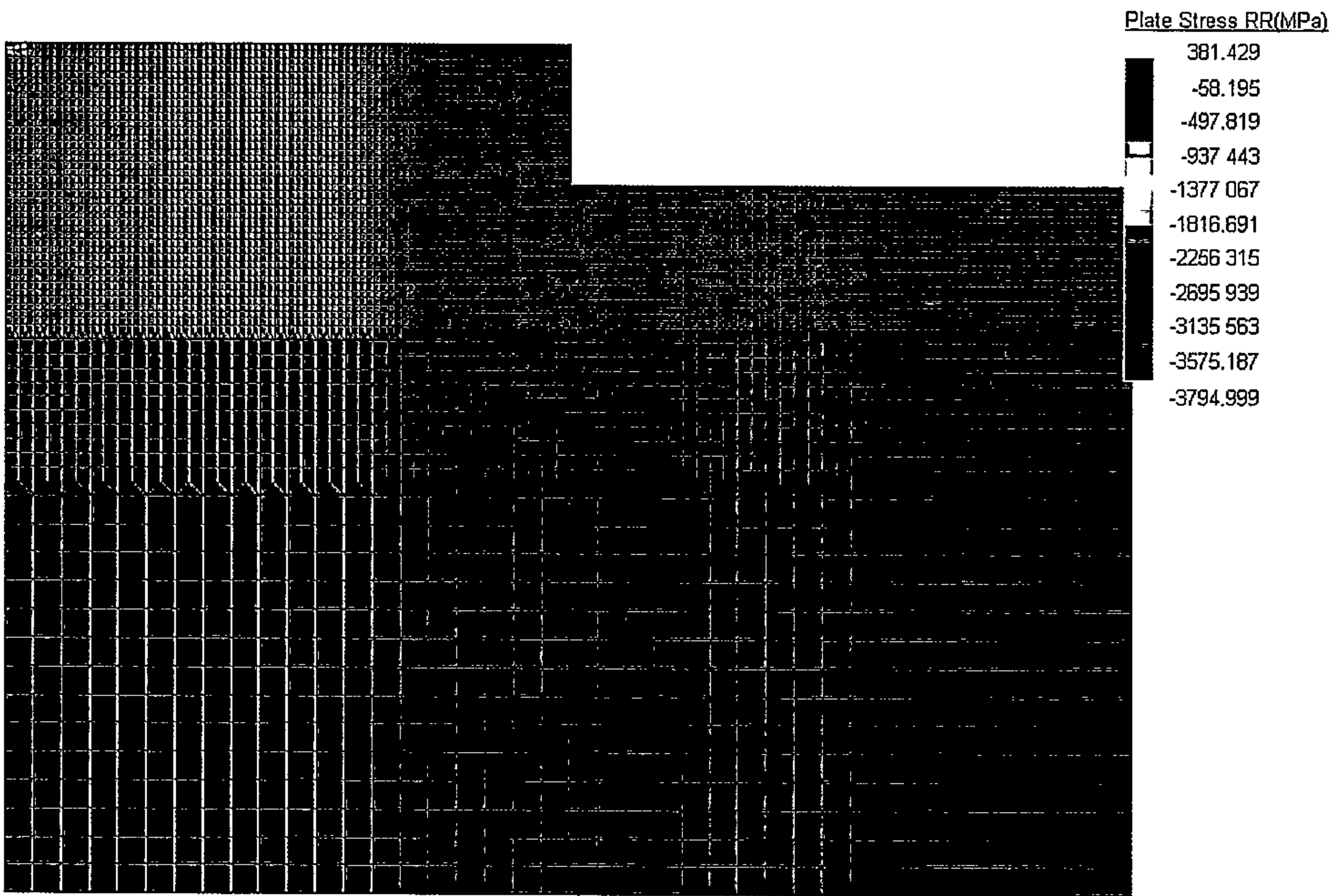


Figure 5.9. Radial Stress (MPa) of disc model, ball loading, on dentine base for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0.

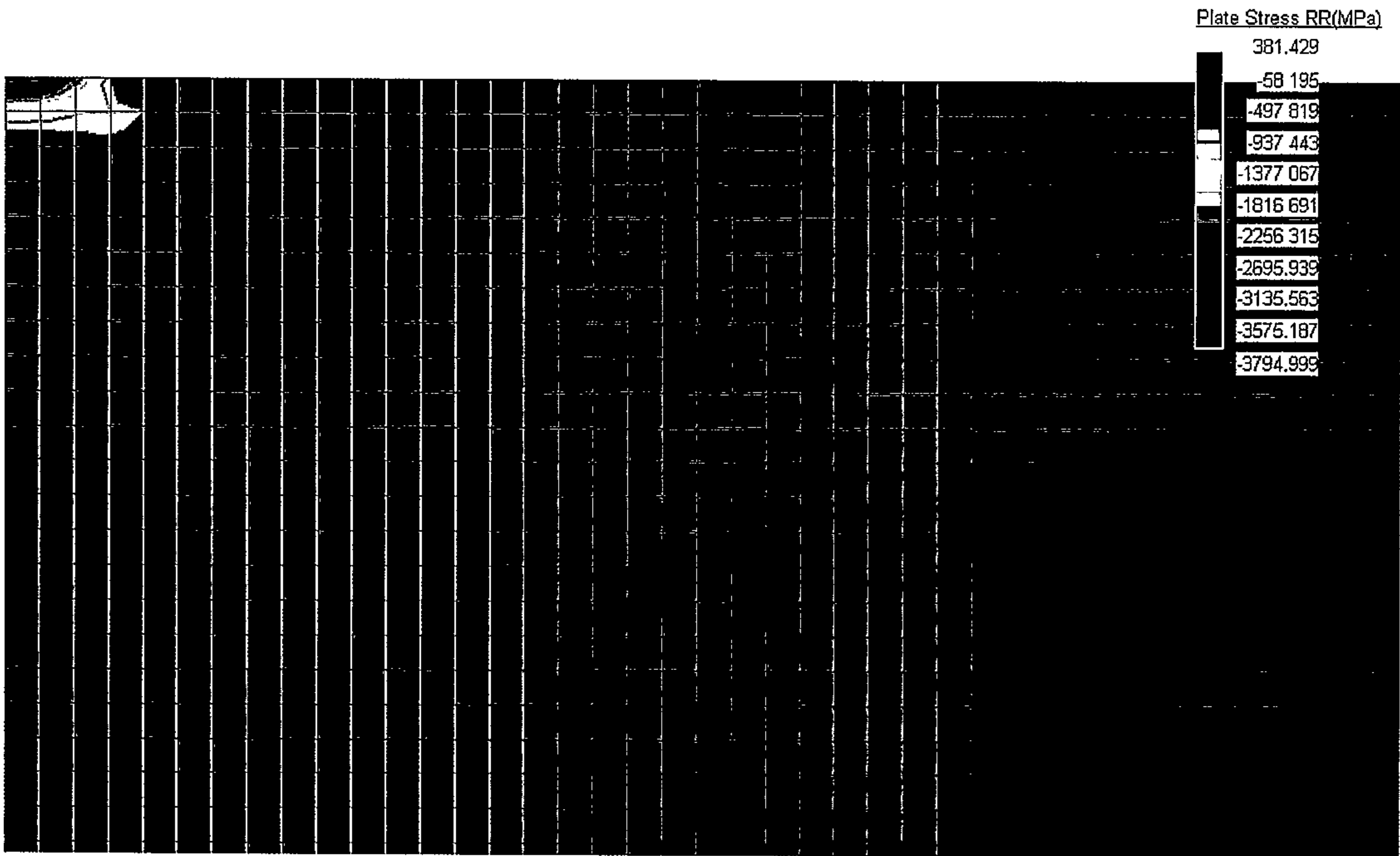


Figure 5.10. Radial Stress (MPa) of disc model centre region for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. Disc on dentine base with ball loading.

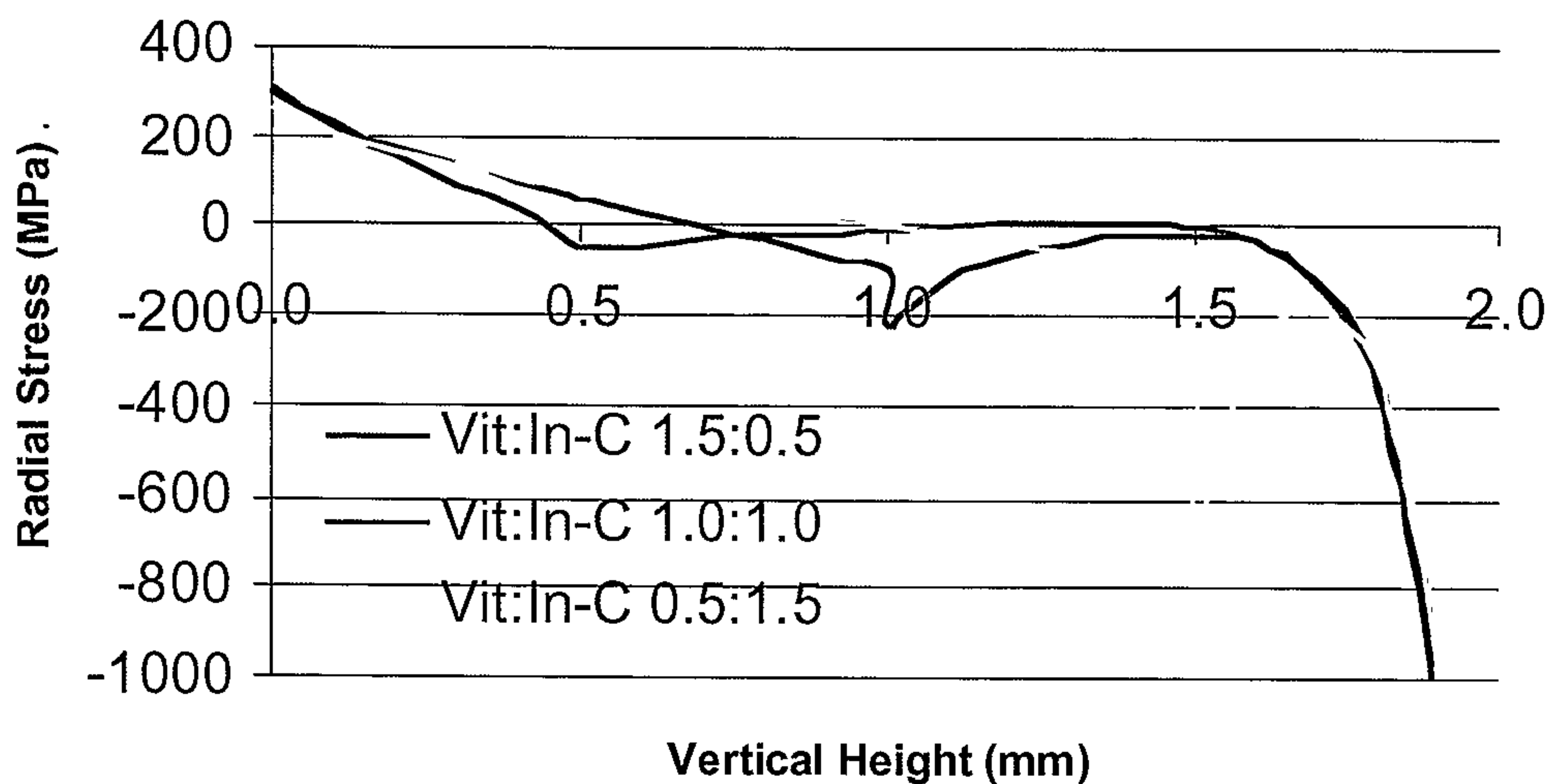


Figure 5.11. Plot of Radial Stresses for each dentine support model; ball loading, with varying thickness of Vitadur to In-Ceram. Stresses measured along the axis of symmetry from bottom surface to top surface.

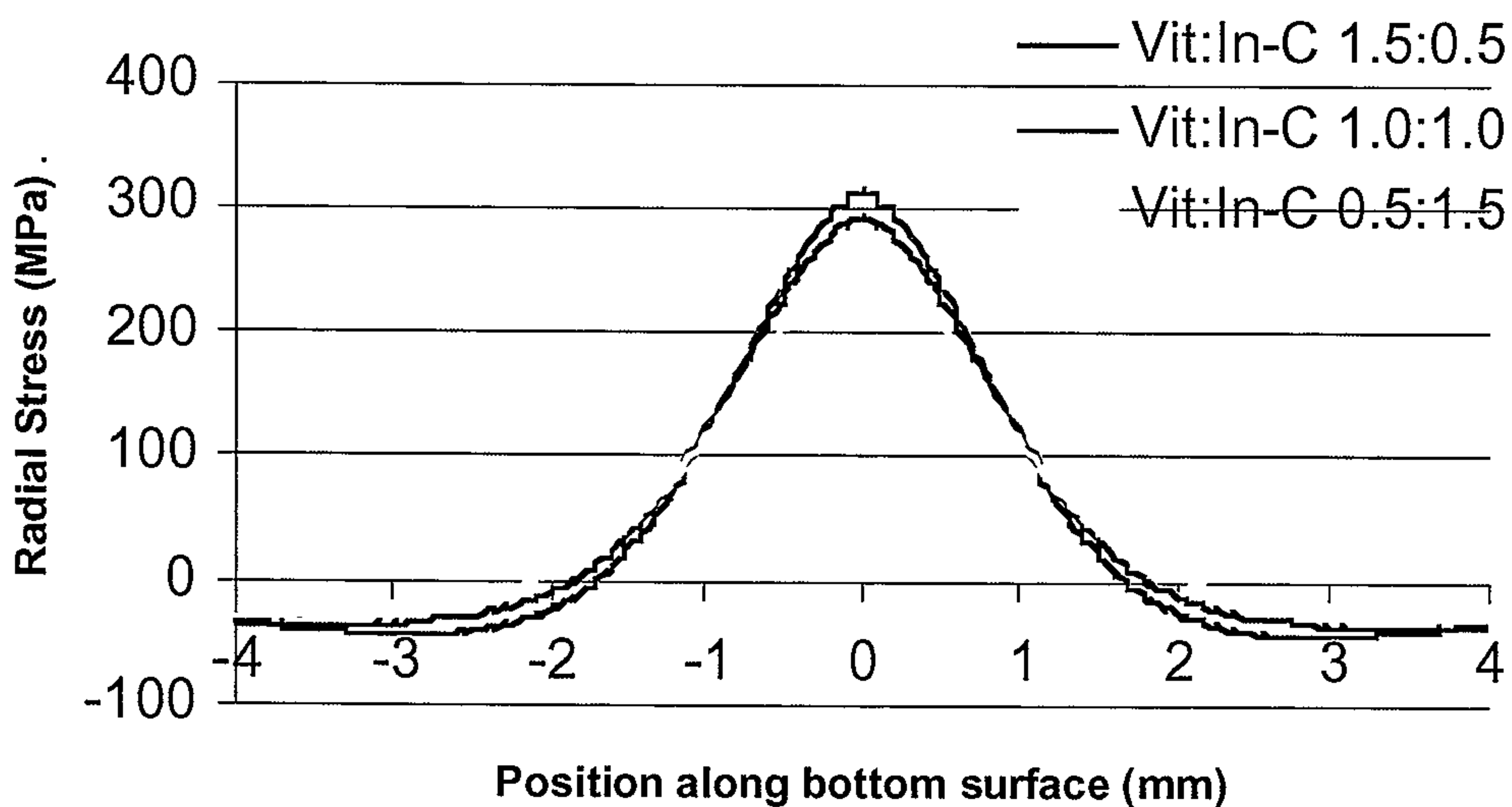


Figure 5.12. Plot of Radial Stresses for dentine support model; ball loading, with varying thickness of Vitadur to In-Ceram. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc.

Figures 5.11 and 5.12 demonstrate the stress levels through the Z – axis and across the bottom surface respectively. These diagrams are for the bilaminar groups only and do not include the monolithic disc models. The compressive stresses on the top surface are much larger than those of the punch test due to the geometry of the indenter and the smaller surface contact area. The bottom surface tensile stresses in figure 5.12 are significantly lower than those seen in figure 5.8 and they are closer together, i.e. the range of values is

not as great. This arises because the load applied to the ball is only 1000 N rather than 1500 N for the punch. The compressive stress that appears at a radius of approximately 1.6 mm from the centre of the disc indicates a positive support from the dentine, whereas the tensile stress in the centre indicates the compliant effect of the dentine to the load. This can only be viewed as a negative effect as it allows the tensile stresses to increase.

5.3.2.3 Steel Support below Biaxial Disc: 5 mm Ball Load

Examples of the stress distributions found when the disc has a rigid support such as steel are seen in figures 5.13 and 5.14. The experimental conditions are the same as above, i.e. 16 mm diameter bilaminar disc of 2 mm thickness, with 1 mm each of Vitadur Alpha and In-Ceram. The load bearing capacity in this system becomes quite high with the mechanical results for the monolithic In-Ceram averaging a 2850 N load. The pattern in the magnified diagram of figure 5.14 which represents one of the bilaminar cases, suggests that the disc is developing surface radial tensile stress to initiate a cone crack and a zone of tension in the Z – axis that could lead to a median crack. This situation was seen in the crown loading situation in chapter 3 and is evident in figure 3.26.

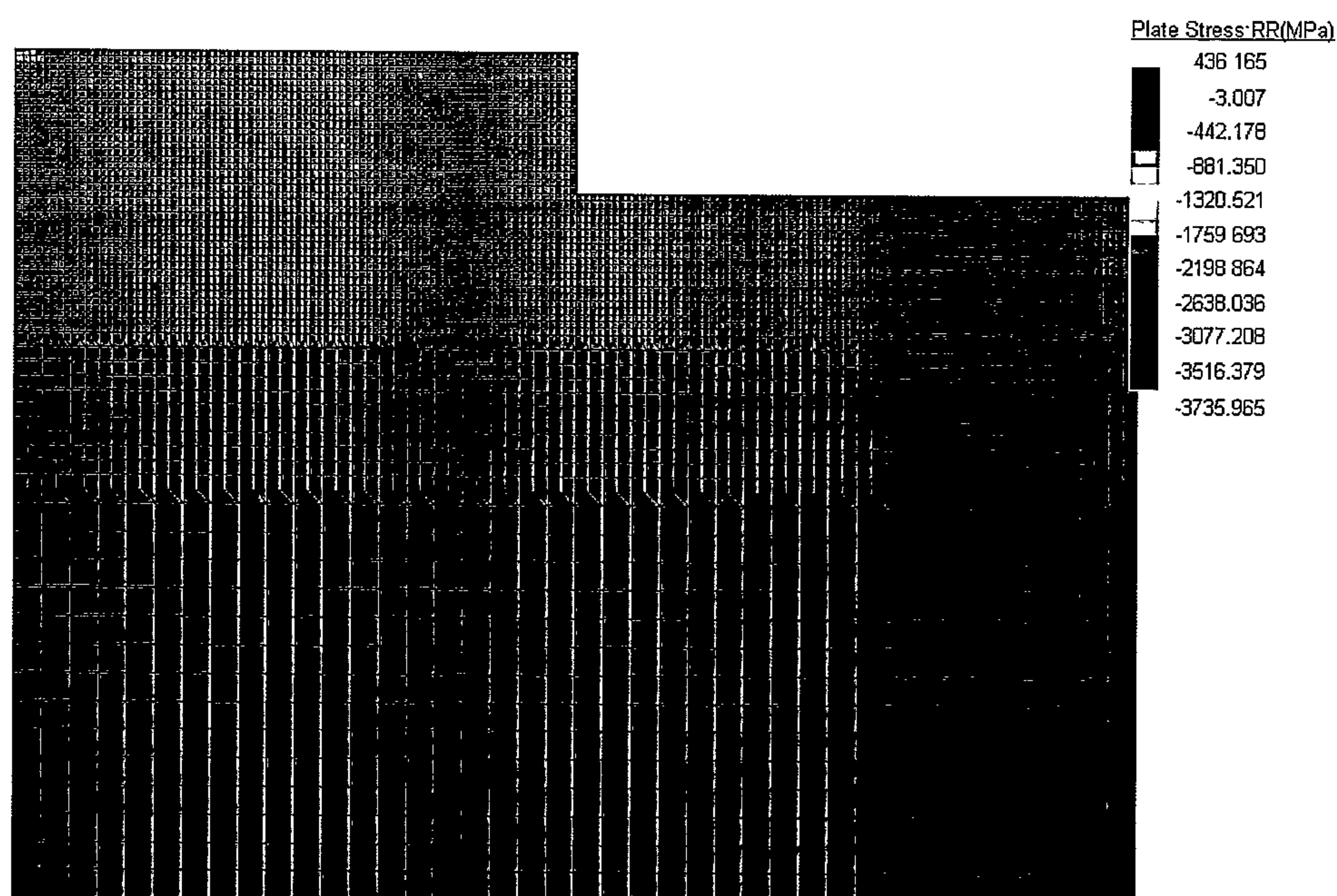


Figure 5.13. Radial Stress (MPa) of disc model, ball loading, on steel base for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. (P = 1000N)

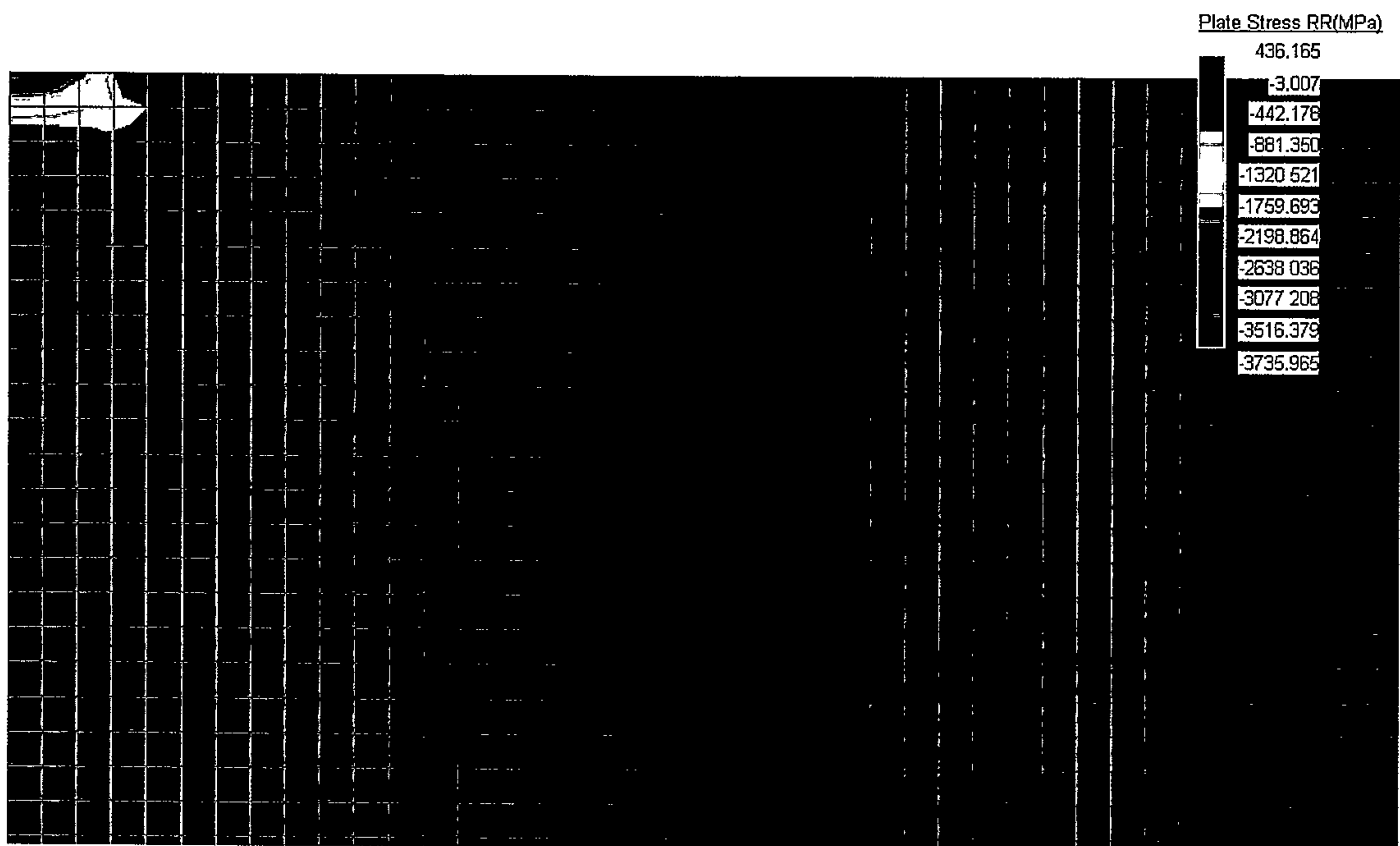


Figure 5.14. Radial Stress (MPa) of disc model centre region for ratio of Vitadur Alpha to In-Ceram Alumina 1.0:1.0. Disc on steel base with ball loading.

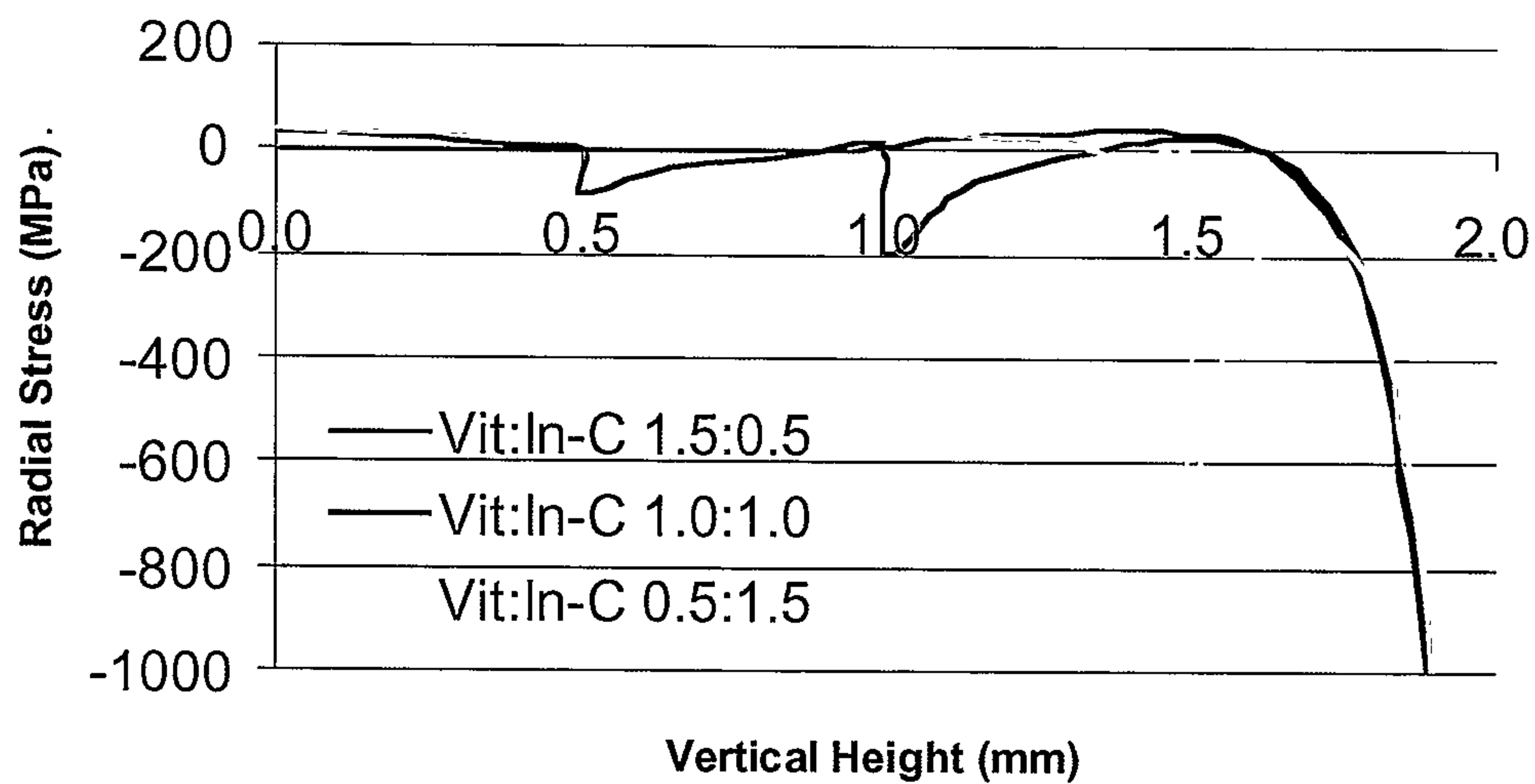


Figure 5.15. Plot of Radial Stresses for each steel support model; ball loading, with varying thickness of Vitadur to In-Ceram. Stresses measured along the axis of symmetry from bottom surface to top surface.

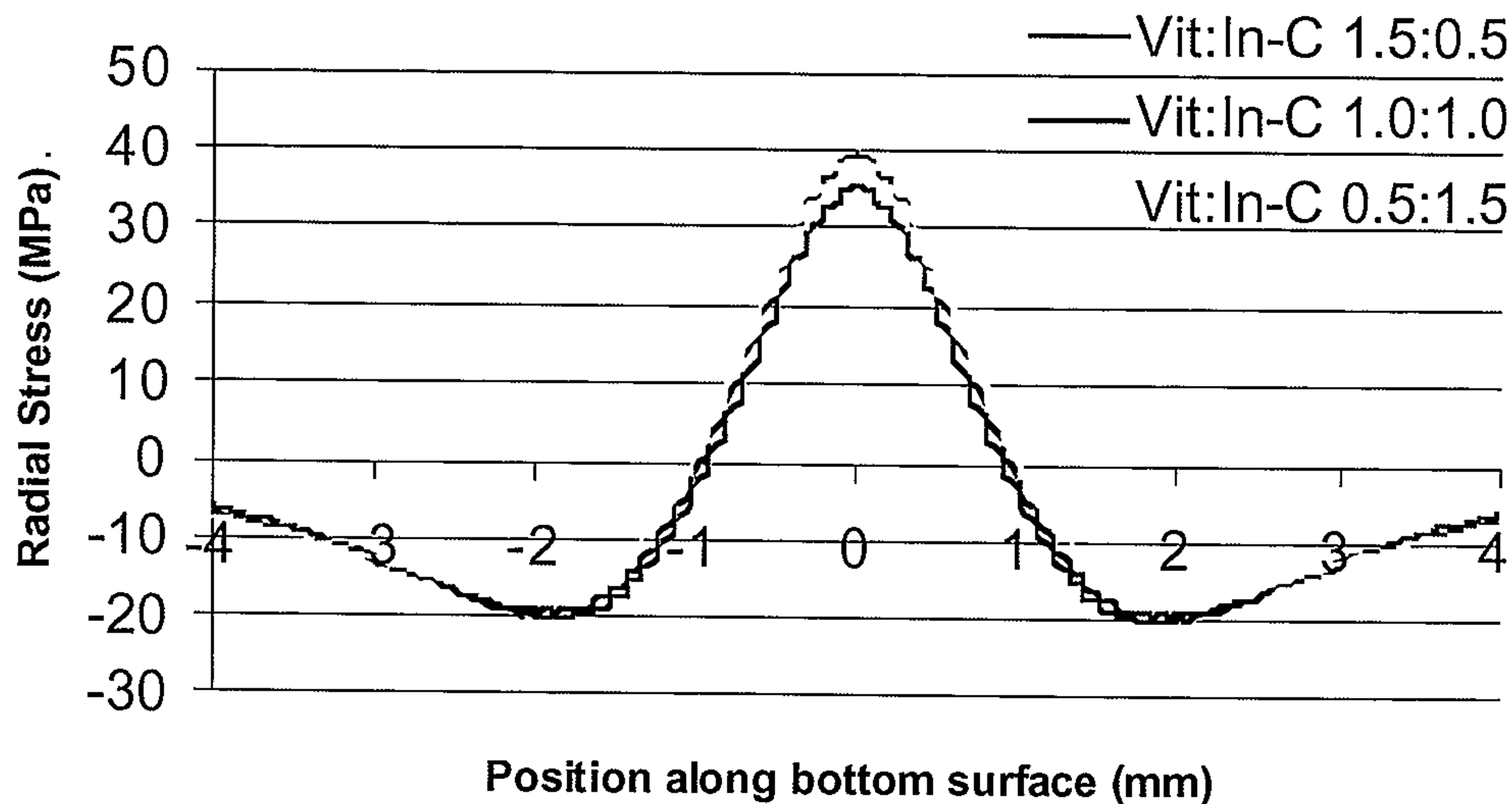


Figure 5.16. Plot of Radial Stresses for ring support model, with varying thickness of Vitadur to In-Ceram. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc.

The plots in figures 5.15 and 5.16 indicate the very significant reduction of the tension in the form of radial stresses along the bottom surface when the support is steel. The magnitude of the tension is approximately 7 to 8 times less than the case for dentine support. The level of compression the disc is experiencing on the lower surface has increased by approximately 2 times. The thicker In-Ceram layer has a more even distribution of stress than the thinner layers.

5.3.2.4. Comparison of like ratios on different support media

This section compares same bilaminar ratios with different support media. The reason is to quantify and thereby appreciate the effect of the support media in protecting the bilaminar structure from fracture.

5.3.2.4.1 Vitadur Alpha: In-Ceram Alumina 1.5:0.5

By transposing the above information, comparison of these stresses can be made amongst each model with the same ratio of Vitadur Alpha to In-Ceram. For each of the three bilaminar ratios, the Finite Element Analysis demonstrated that the stiffer the support the better the performance of each particular bilaminate. The results also show that the thicker the In-Ceram, the lower the tensile stress on the bottom surface and the higher the compressive stress at the interface. These results are seen in the plots in figures 5.17 to 5.22.

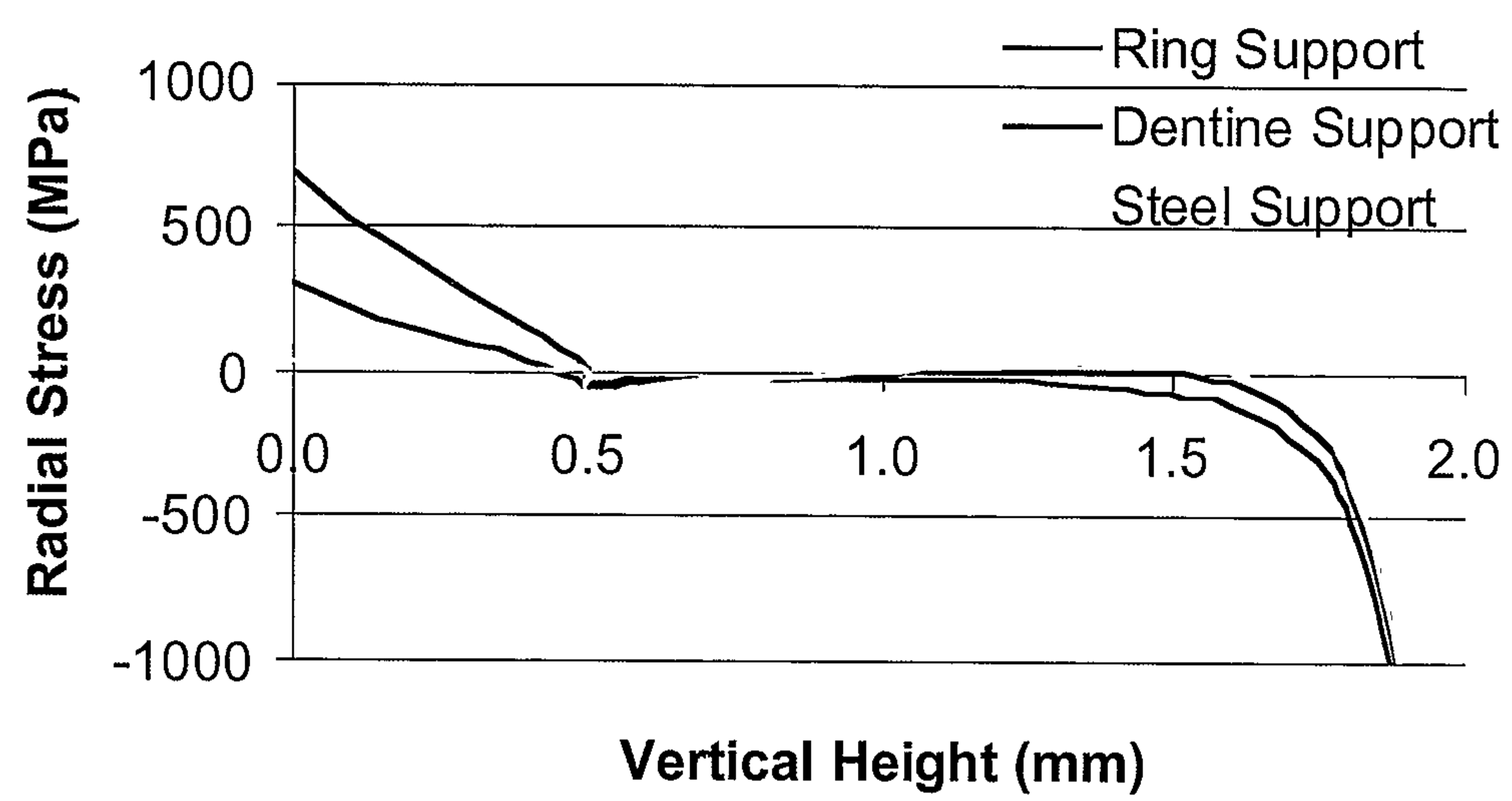


Figure 5.17. Plot of Radial Stresses of each Vitadur Alpha : In-Ceram 1.5:0.5 ratio model, with different support conditions. Stresses measured along the axis of symmetry from bottom surface to top surface. Ball loading, $P = 1000$ N.

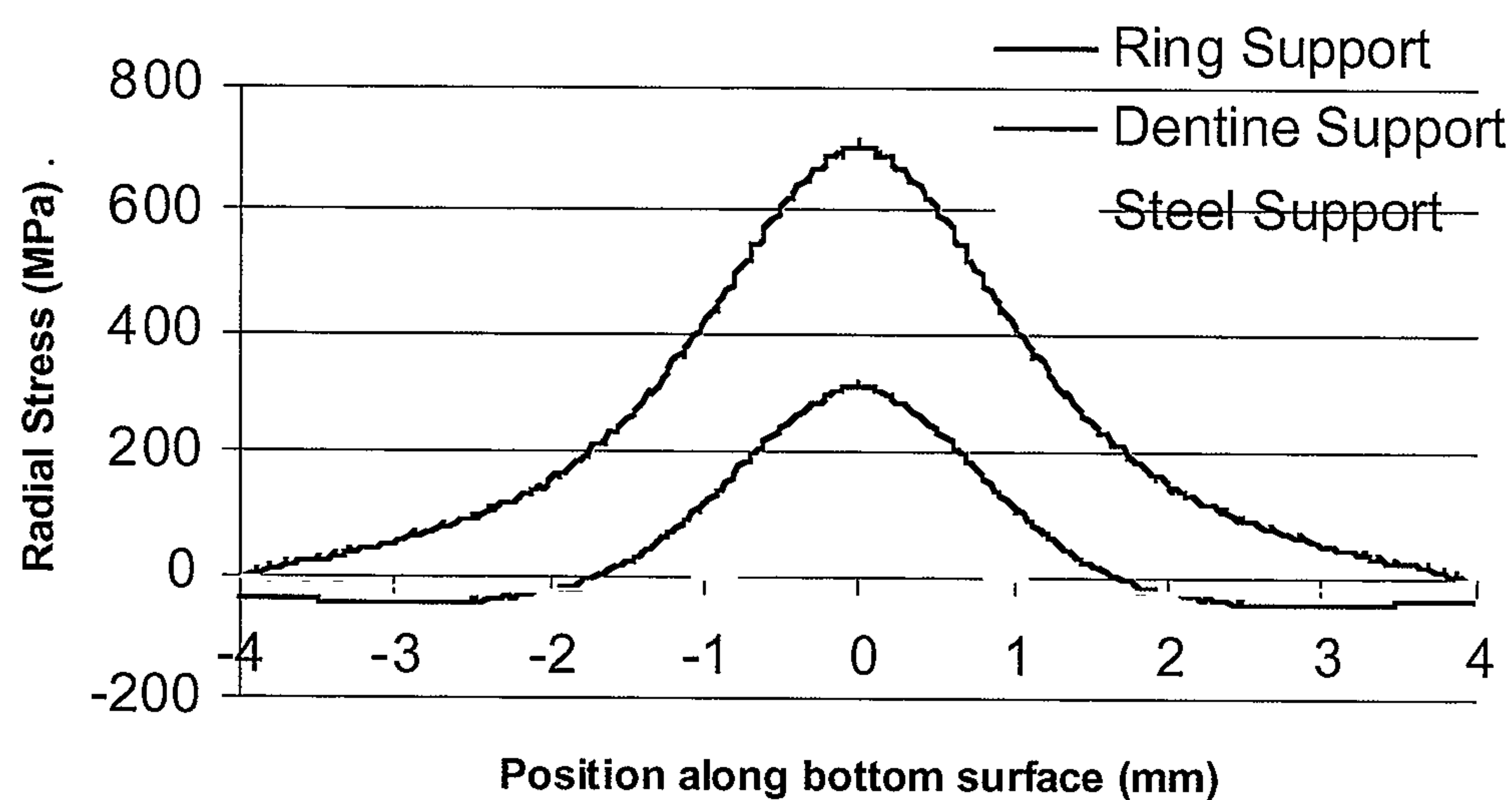


Figure 5.18. Plot of Radial Stresses of each Vitadur Alpha: In-Ceram 1.5:0.5 ratio model, with different support conditions. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc. Ball loading, $P = 1000$ N.

5.3.2.4.2 Vitadur Alpha: In-Ceram Alumina 1.0:1.0

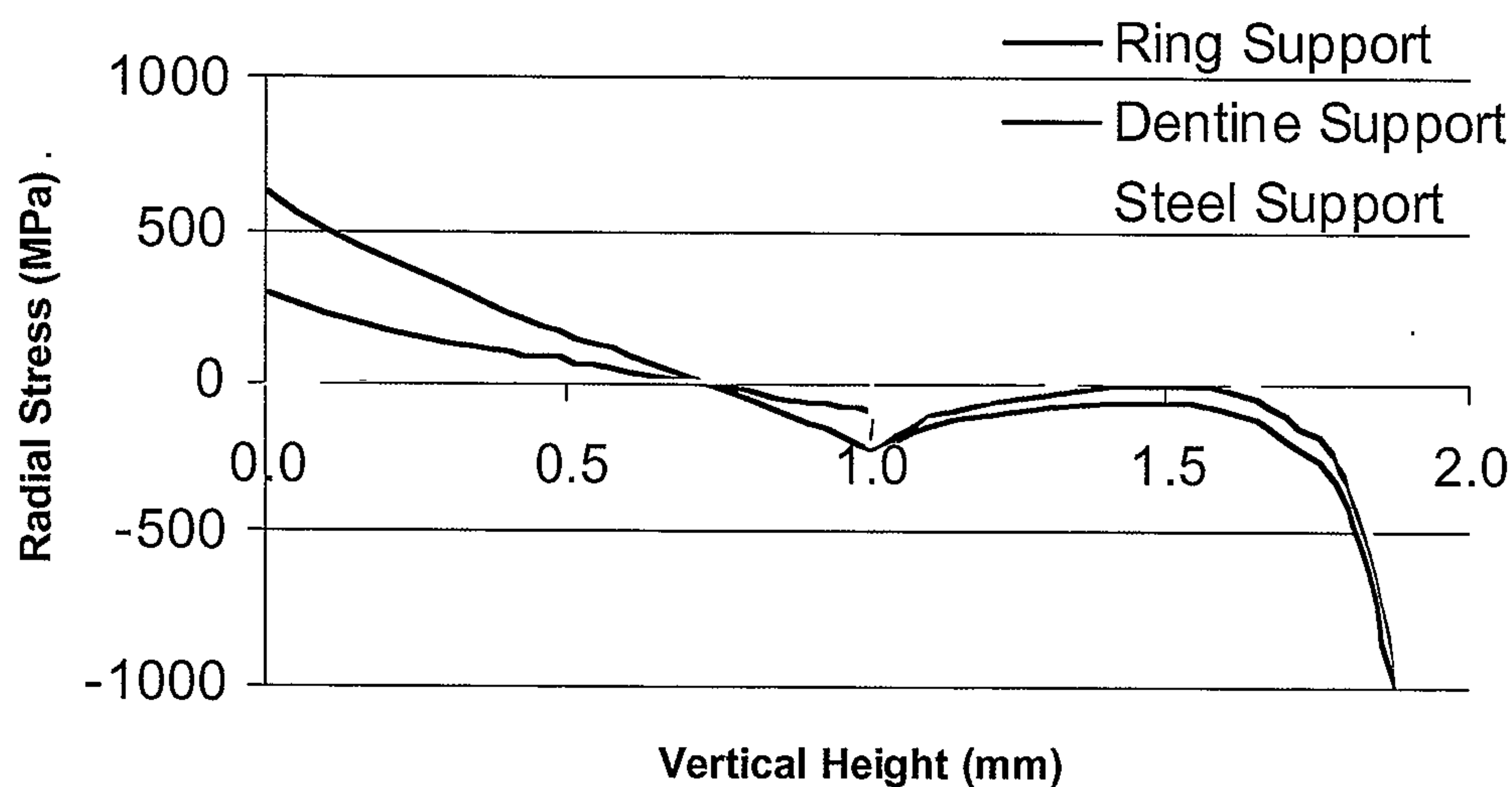


Figure 5.19. Plot of Radial Stresses of each Vitadur Alpha : In-Ceram 1.0:1.0 ratio model, with different support conditions. Stresses measured along the axis of symmetry from bottom surface to top surface.

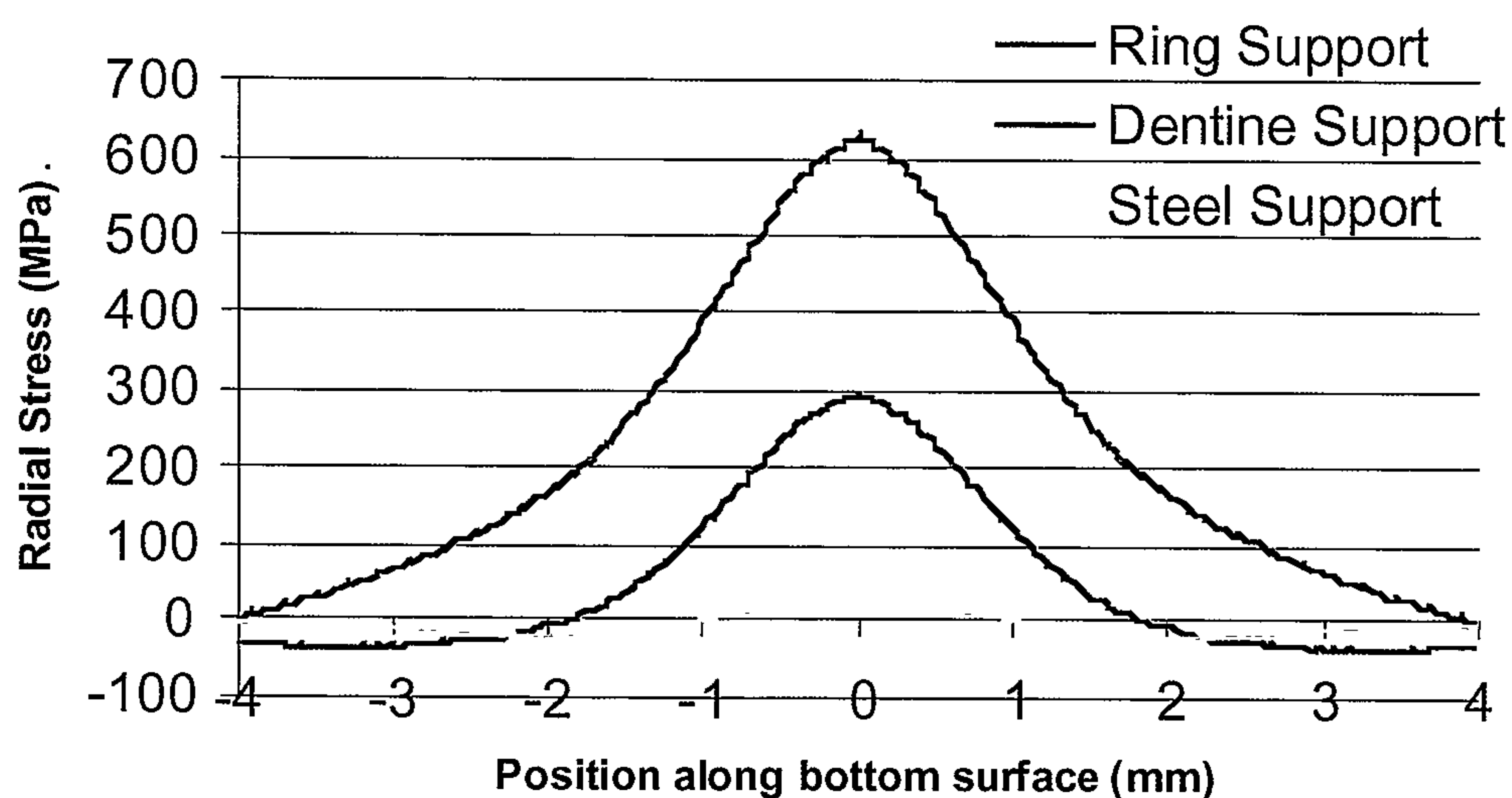


Figure 5.20. Plot of Radial Stresses of each Vitadur Alpha:In-Ceram 1.0:1.0 ratio model, with different support conditions. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc.

5.3.2.4.3 Vitadur Alpha:In-Ceram Alumina 0.5:1.5

The plots in figures 5.21 and 5.22 give particular emphasis to the supportive nature of the thicker In-Ceram with high compressive stresses at the interface between the porcelain and the ceramic and lower tensile stresses across the undersurface. The result when comparing the tensile stress on dentine for figure 5.20 and 5.22 demonstrates a small but appreciable

trend for the increased thickness of In-Ceram to have less tensile stress on the undersurface.

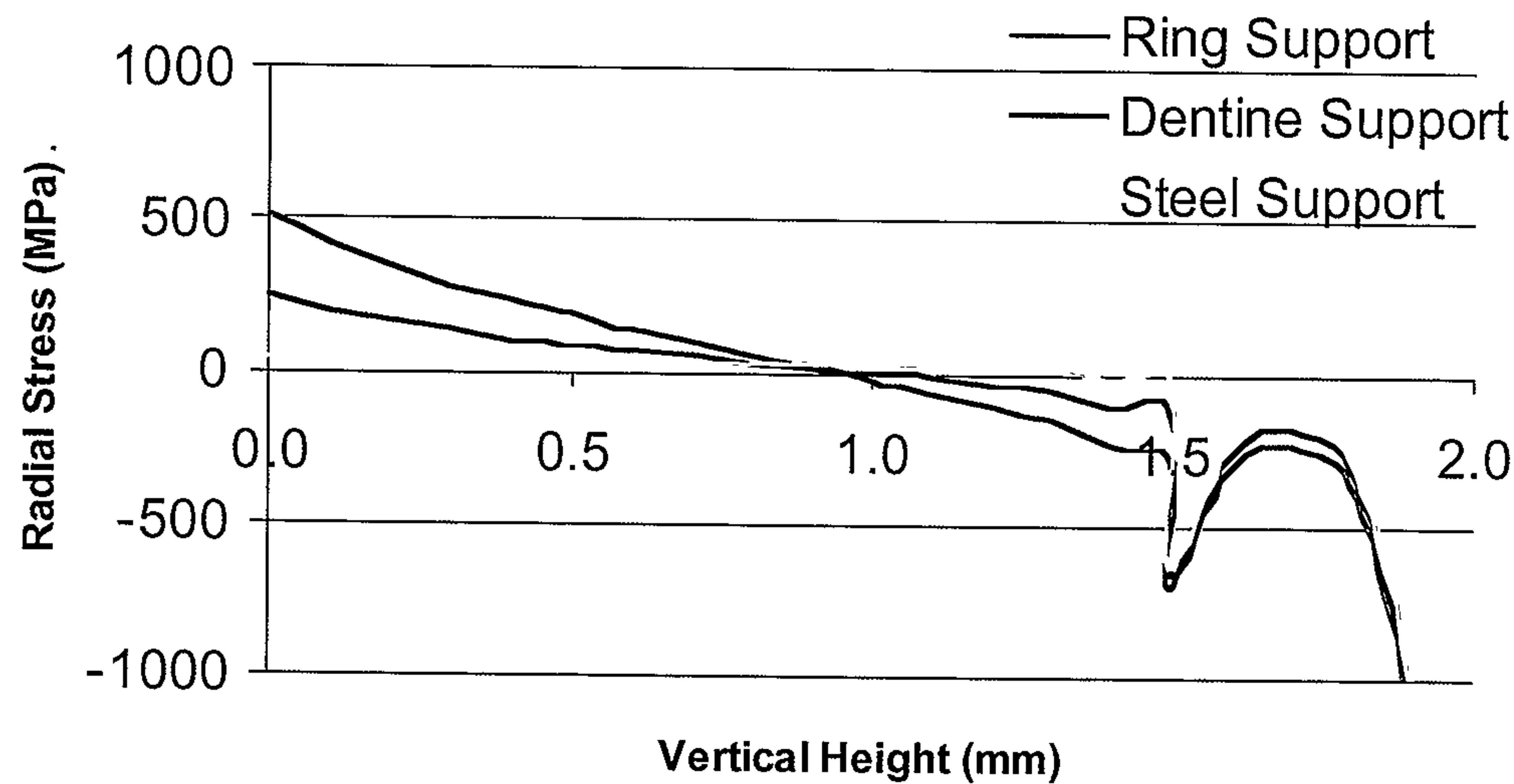


Figure 5.21. Plot of Radial Stresses of each Vitadur:In-Ceram 0.5:1.5 ratio model, with different support conditions. Stresses measured along the axis of symmetry from bottom surface to top surface.

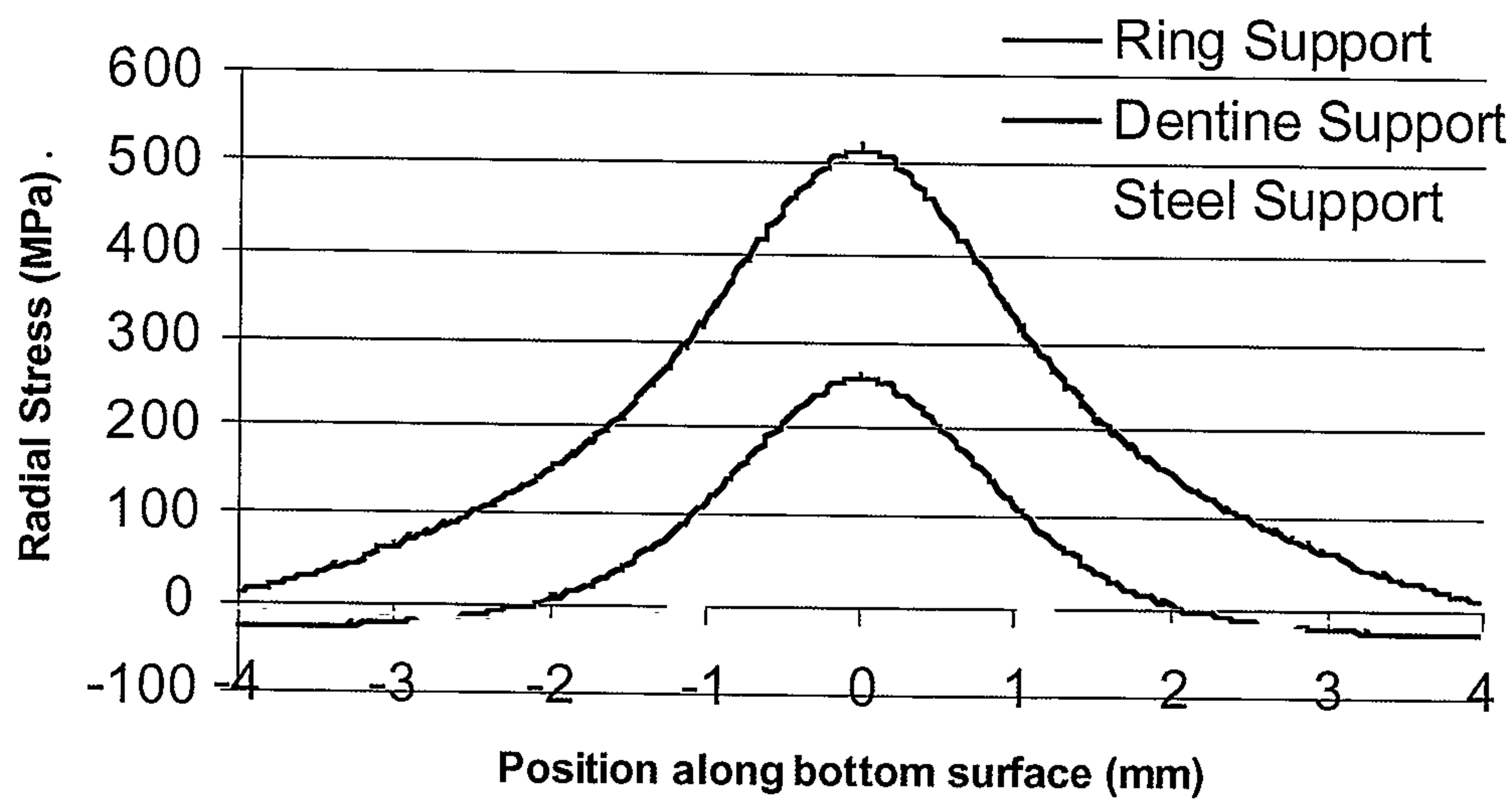


Figure 5.22. Plot of Radial Stresses of each Vitadur Alpha:In-Ceram 0.5:1.5 ratio model, with different support conditions. Stresses measured along the bottom of surface between a radius of 4 mm across the centre of the disc.

5.3.3 Results from the Analytical Stress Analysis.

A comparison of the principal radial tensile stress results on the top surface using the “Elastica” program for stress analysis of the samples tested with the 5 mm ball indenter

against a flat steel support of infinite thickness are listed in table 5.3. Examples of the plots for the 2 mm thick Vitadur Alpha discs, the 2 mm In-Ceram discs and the 2 mm bilaminar discs are included below. In each of these situations the actual stress at failure was calculated, not at a nominal force as for the FEA investigation.

The first result demonstrated in figure 5.23 provides an indication of the stresses developed below the 5 mm ball indenter in a 2 mm thick In-Ceram disc supported by a steel base. The contact area has a high compressive stress field immediately below it but at deeper levels directly below the contact this compressive stress field rapidly disappears. As is expected lower tensile stresses develop on the surface about the contact area. These decrease with radius and depth below the surface.

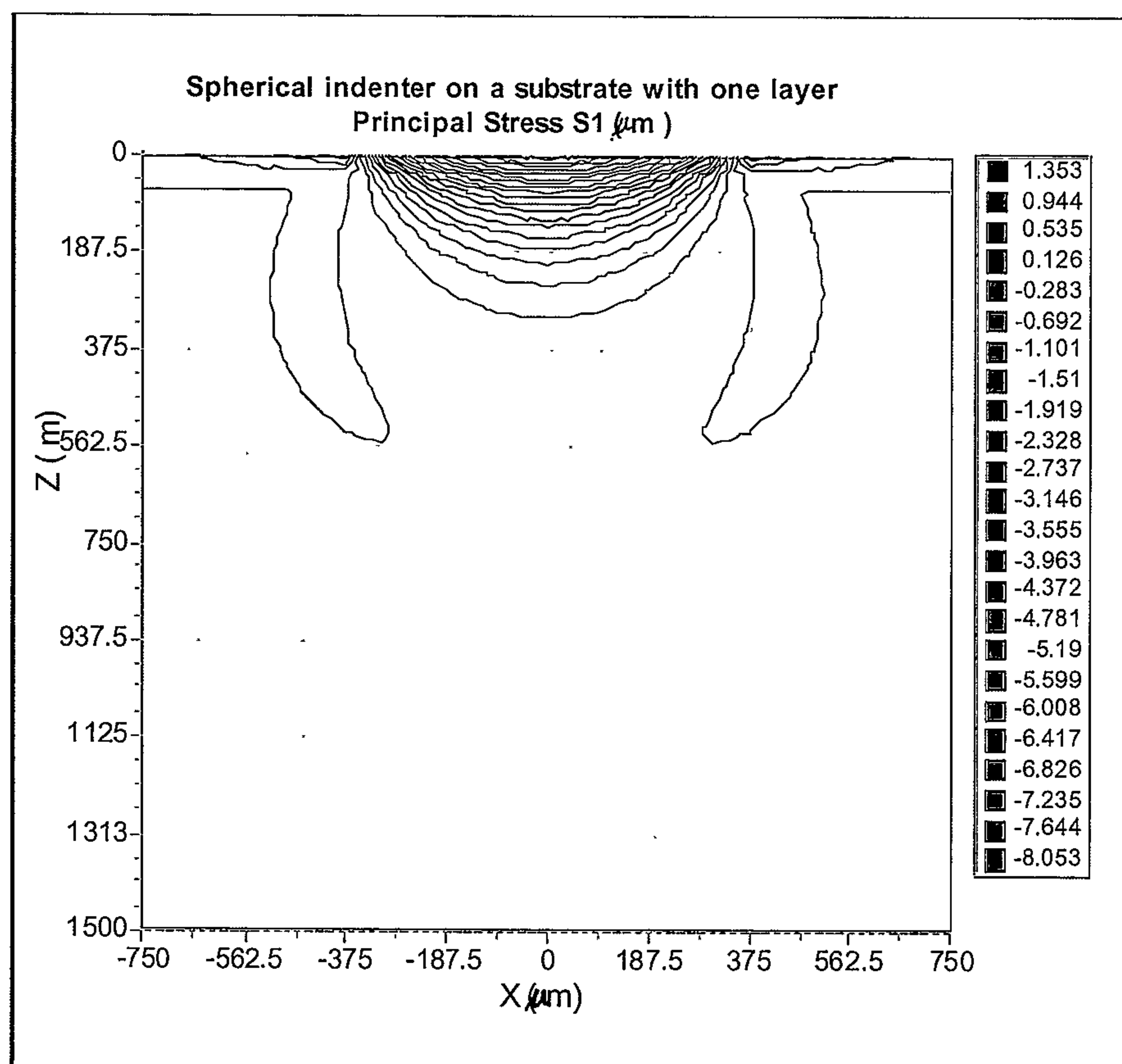


Figure 5.23 Elastic stress plot for the principal stresses below the surface at the contact area for a 5 mm ball indenter on a 2 mm thick In-Ceram disc supported by a flat steel base. The average load at failure was 2825 N and the maximum tensile stress was 1775 MPa.

The principal stress field across the contact surface is demonstrated in figure 5.24 below. The stress distribution has a sharp demarcation between the compressive stresses beneath the indenter and the tensile stresses generated just beyond the contact radius which was

calculated to be 356 μm in this case. The peak principal tensile stress just outside this radius was 1775 MPa. High compressive stresses can be seen below the centre of contact of the indenter in figure 5.24 with the peak demonstrated at the bottom of the curve.

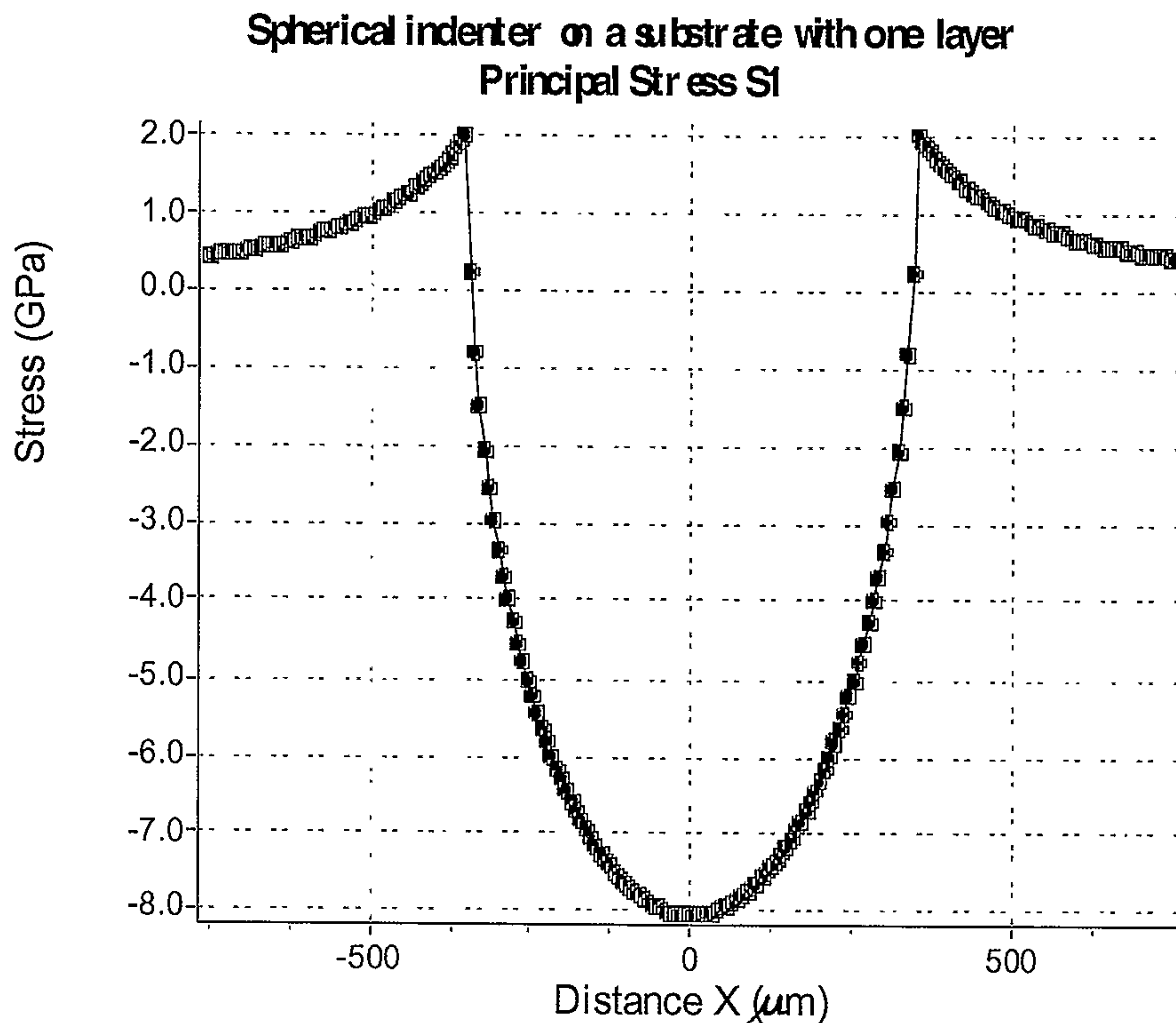


Figure 5.24 The principal stress distribution below the 5 mm diameter ball indenter on the below the top surface of a 2 mm thick In-Ceram disc. ($P = 2825 \text{ N}$)

The following example demonstrates the situation for the 2 mm thick Vitadur Alpha case. The average load at failure from the analogue data was 736 N and contact radius was 292 μm . This is compared with 2850 N as the average load at failure for In-Ceram at a contact radius of 356 μm . The principal tensile stress for the Vitadur Alpha was 638 MPa and for In-Ceram it was 1775 MPa. This indicates that under these support conditions a disc or crown made entirely from In-Ceram can sustain extremely high contact loads from a high modulus spherical indenter before failure. These loads are far in excess of those expected in the mouth. The significance is that under normal oral conditions the In-Ceram would experience the stiffest contacts when loaded against gold or porcelain. The elastic moduli for these antagonists would range between 70 and 120 GPa. Occasionally the contact may be against a cobalt-chrome section of a partial denture where the elastic modulus could be expected to be of the same order as the steel ball indenter. Under these latter conditions however, contact with Vitadur Alpha is likely to produce sufficient stresses to induce fracture.

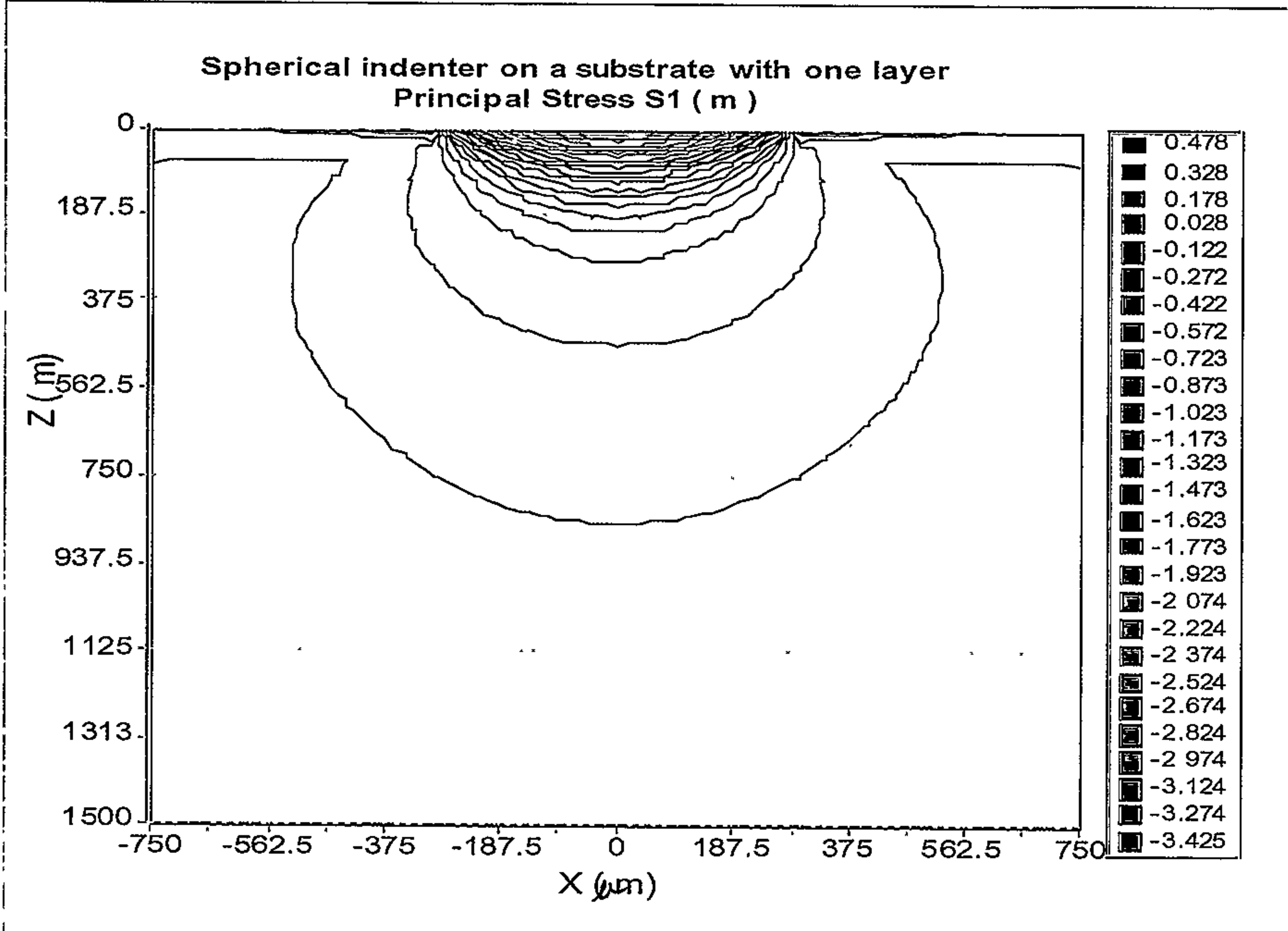


Figure 5.25 Elastica stress plot for the principal stresses below the surface at the contact area for a 5 mm ball indenter on a 2 mm thick Vitadur Alpha disc supported by a flat steel base. (P = 736 N) Contact radius 292 μm.

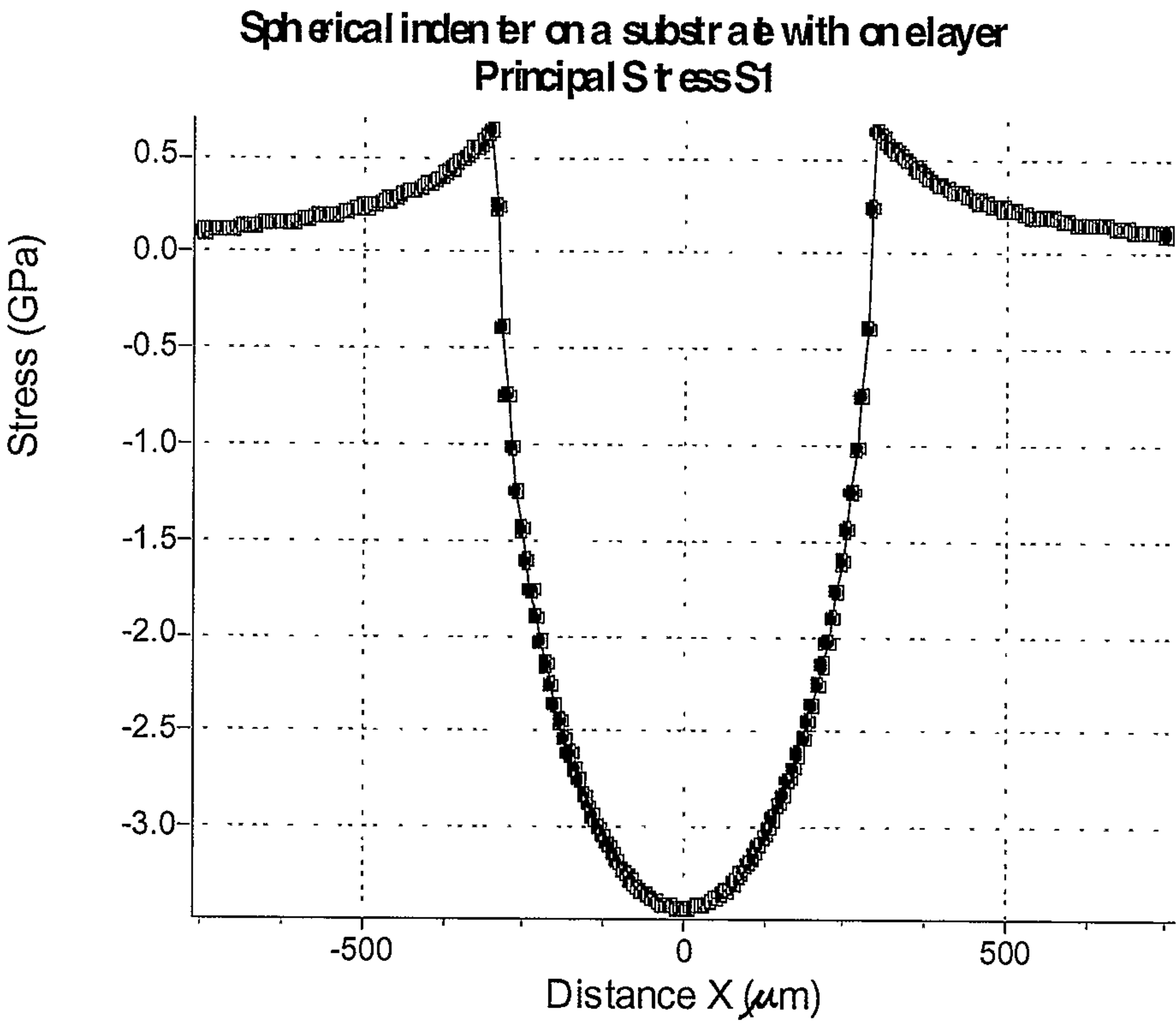


Figure 5.26 The principal stress distribution below the 5 mm diameter ball indenter on the top surface (X-axis) of a 2 mm thick Vitadur Alpha disc. (P = 736 N; Contact radius 292 μm)

The discs that are made from the two materials exhibit different responses with higher contact radii than might be expected for the given force on the Vitadur Alpha top layer. The principal tensile stress on the lower surface is still within expected limits with the exception of group 2 where it is considerably higher. It is possible that a more complex crushing procedure is taking place in this example and the resultant smear of crushed porcelain creates a wider contact radius.

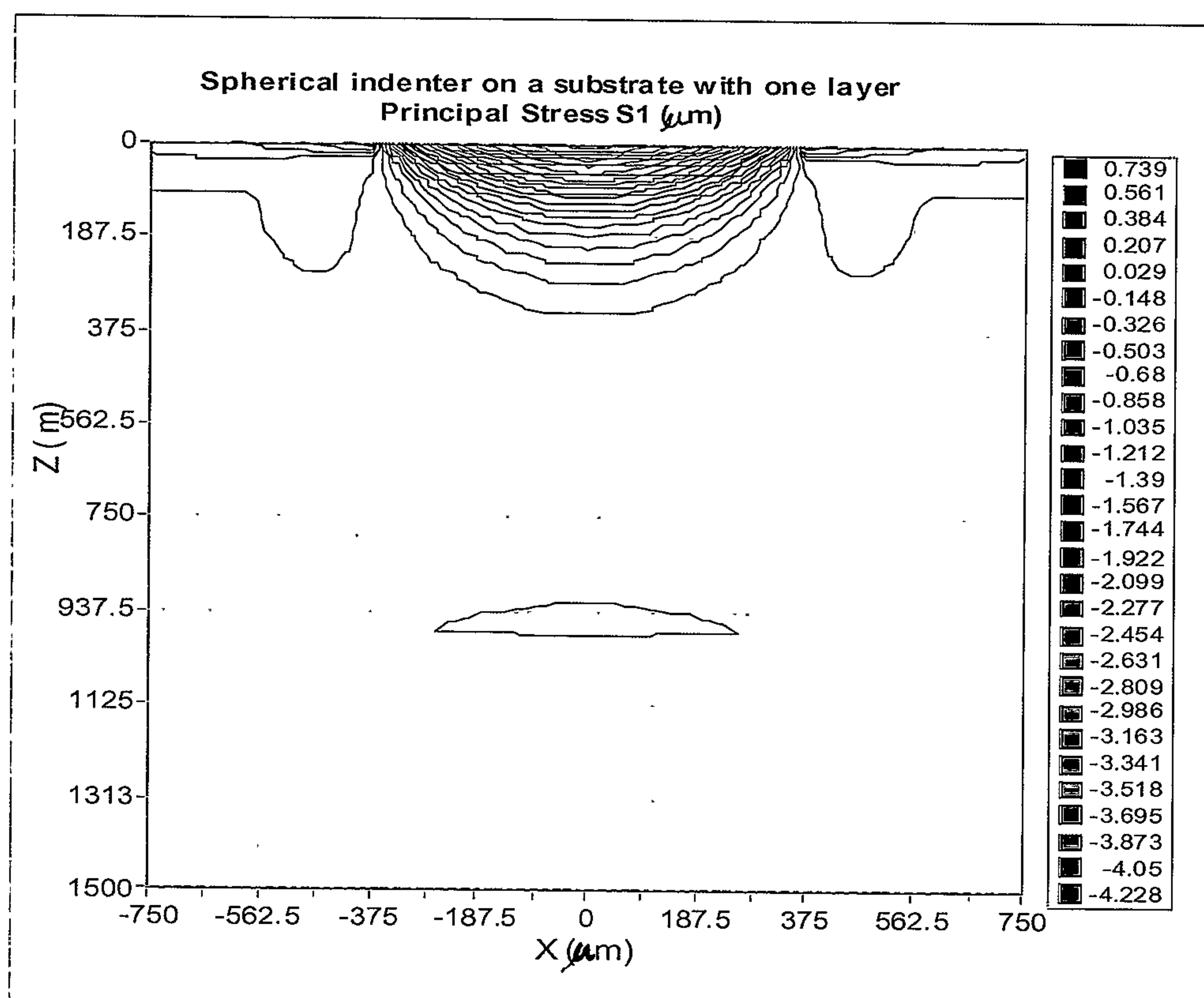


Figure 5.27 The stress distribution below the 5 mm diameter ball indenter on the top surface (X-axis) of a 1 mm thick layer of Vitadur Alpha on 1 mm In-Ceram base disc. The maximum tensile stress was 974 MPa. ($P = 1589 \text{ N}$; Contact radius, $366 \mu\text{m}$)

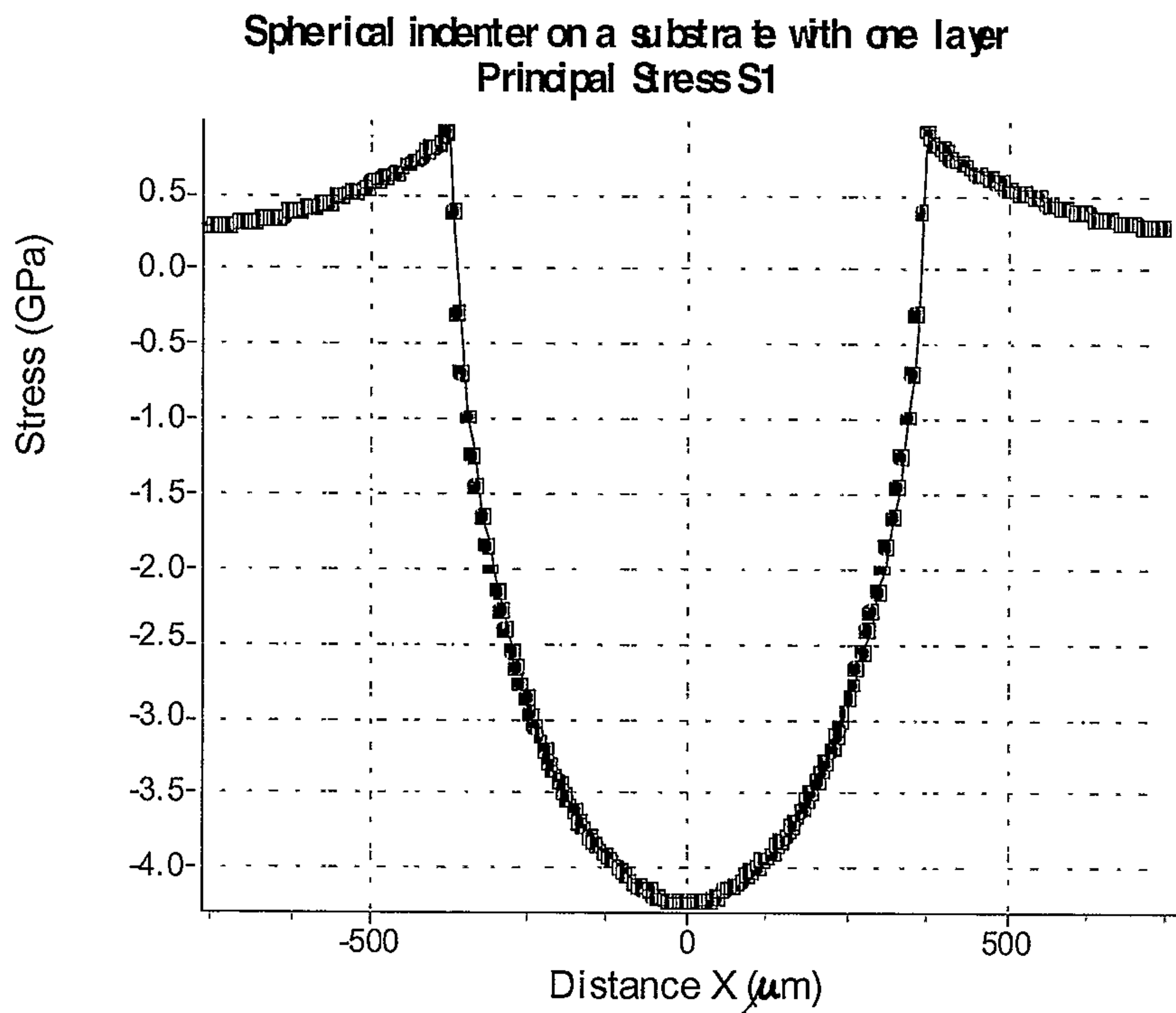


Figure 5.28 The Principal stress distribution below the 5 mm diameter ball indenter on the top surface (X-axis) of a 1 mm thick layer of Vitadur Alpha on 1 mm In-Ceram base disc. (P = 1589 N; Contact radius, 366 μm)

The results from this analysis are included in table 5.3. The stress distributions for the final three groups (groups 6, 7, and 8) are displayed below. The most important feature is the strong discrepancy in stress distribution that occurs at the interface between the overlying Vitadur Alpha veneer and the In-Ceram core material for the thinnest veneer layer. These results are for the fully supported discs.

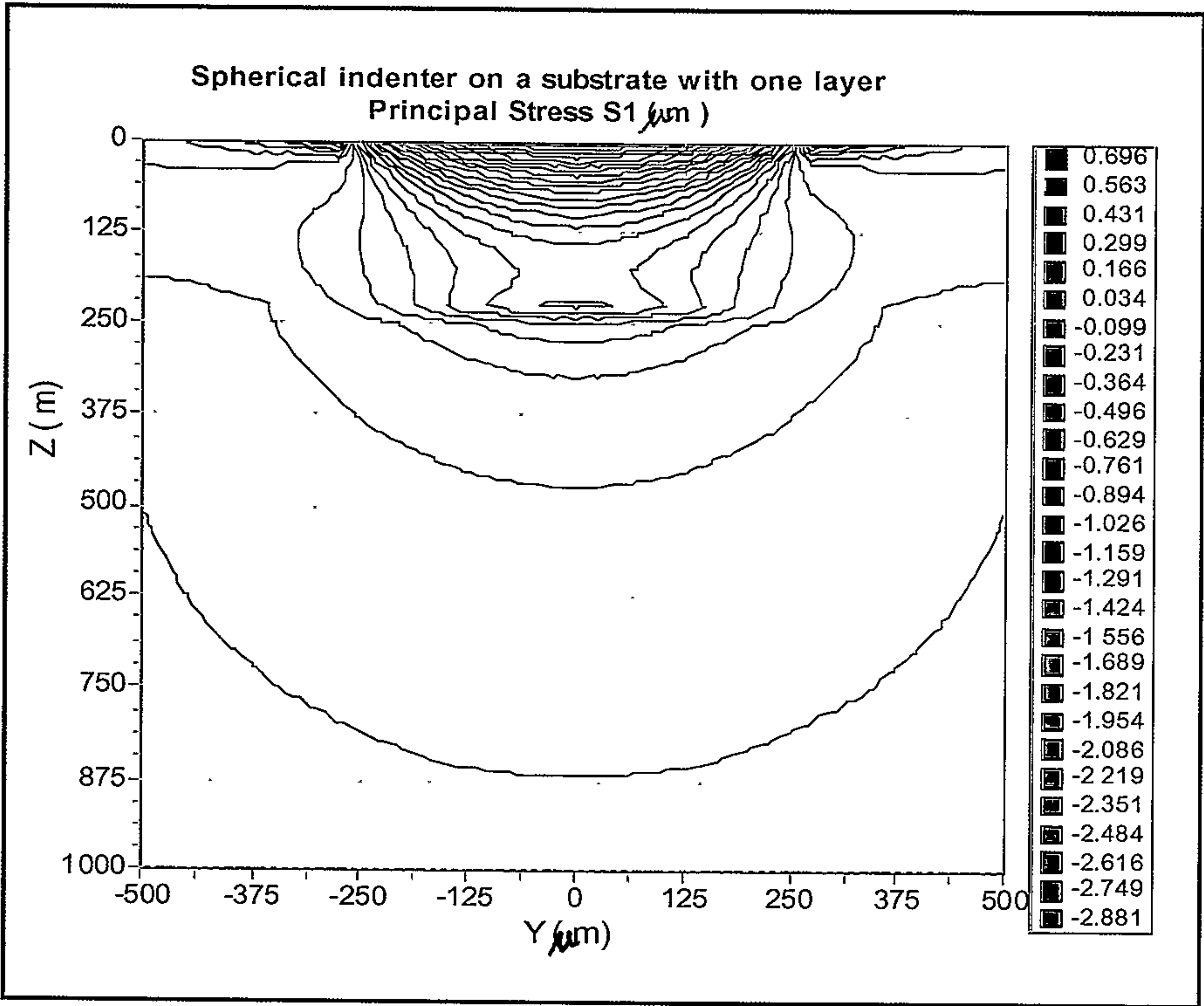


Figure 5.29 Principal stress distribution for 0.25 mm Vitadur Alpha on 1 mm In-Ceram ($P = 681.6\text{ N}$; Contact radius, $265\text{ }\mu\text{m}$)

The figure above (5.29) provides a diagram of the calculated stress distribution for the 5 mm ball indenter on the top surface of a bilaminar disc that has 0.25 mm Vitadur Alpha as the veneer and 1 mm In-Ceram beneath. The disc model was supported by steel. Under these contact conditions where the Elastic modulus and Poisson’s ratio of all components were taken into account, the calculated stresses indicate very high contact pressure and compressive stresses below the indenter and a weaker compressive contact stress at the interface. The average load at fracture was 681.6 N. The program also calculates the contact radius, which for this condition was $265\text{ }\mu\text{m}$. At the edges of the contact circle, the stress undergoes a steep change from compressive to tensile as would be expected for a Hertzian contact condition. This change for the x -axis has been plotted in figure 5.30 below. The maximum stress for this condition was 861 MPa and these results are recorded in table 5.3.

The third figure for this condition (5.31) demonstrates the principal stresses in the z – axis directly below the indenter. This plot has a gradient that also reflects the strong compression at the surface followed by a rapid reduction as the veneer is penetrated, the In-Ceram core shows slight tensile stress which decreases as the interface is approached. This condition confirms the high damage level that occurs in the veneer layer beneath the indenter during testing. The region below the contact suffers severe crushing. The crushed

condition makes further calculation of stresses in the In-Ceram layer difficult because the material properties of this now smear layer are hard to measure.

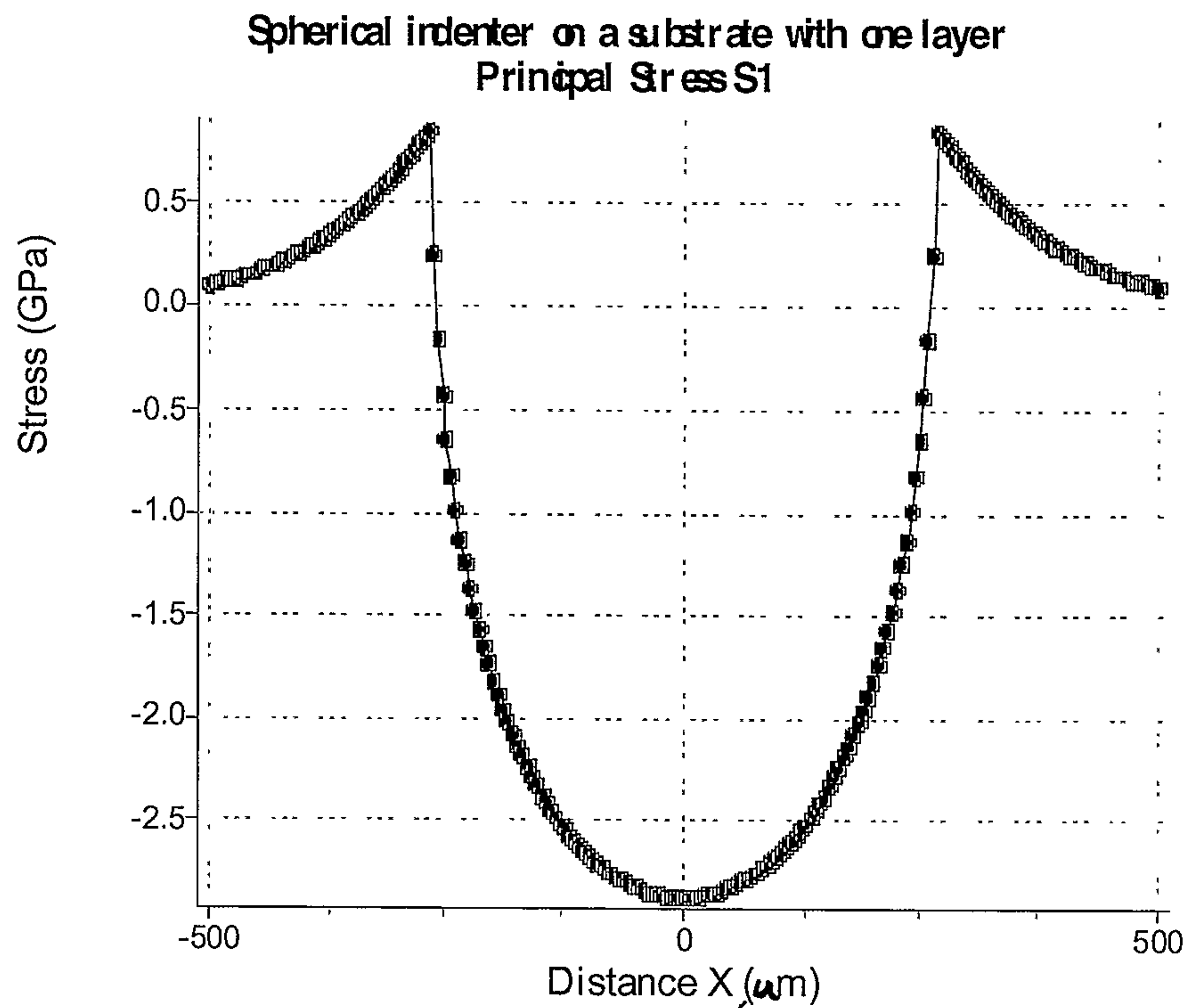


Figure 5.30 Principal stress distribution for 0.25 mm Vitadur Alpha on 1 mm In-Ceram in the X-axis.

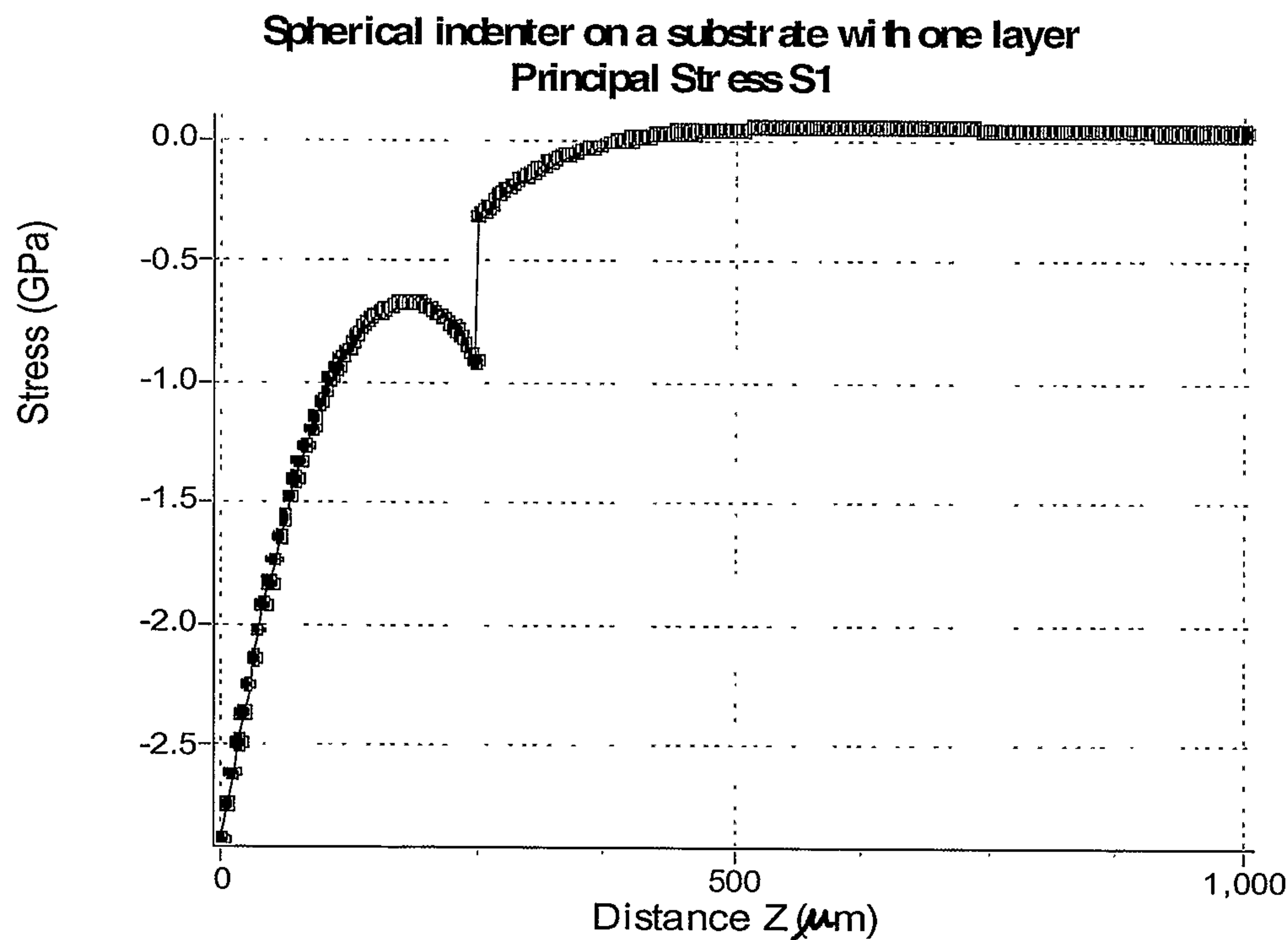


Figure 5.31 Principal stress distribution for 0.25 mm Vitadur Alpha on 1 mm In-Ceram in the Z-axis.

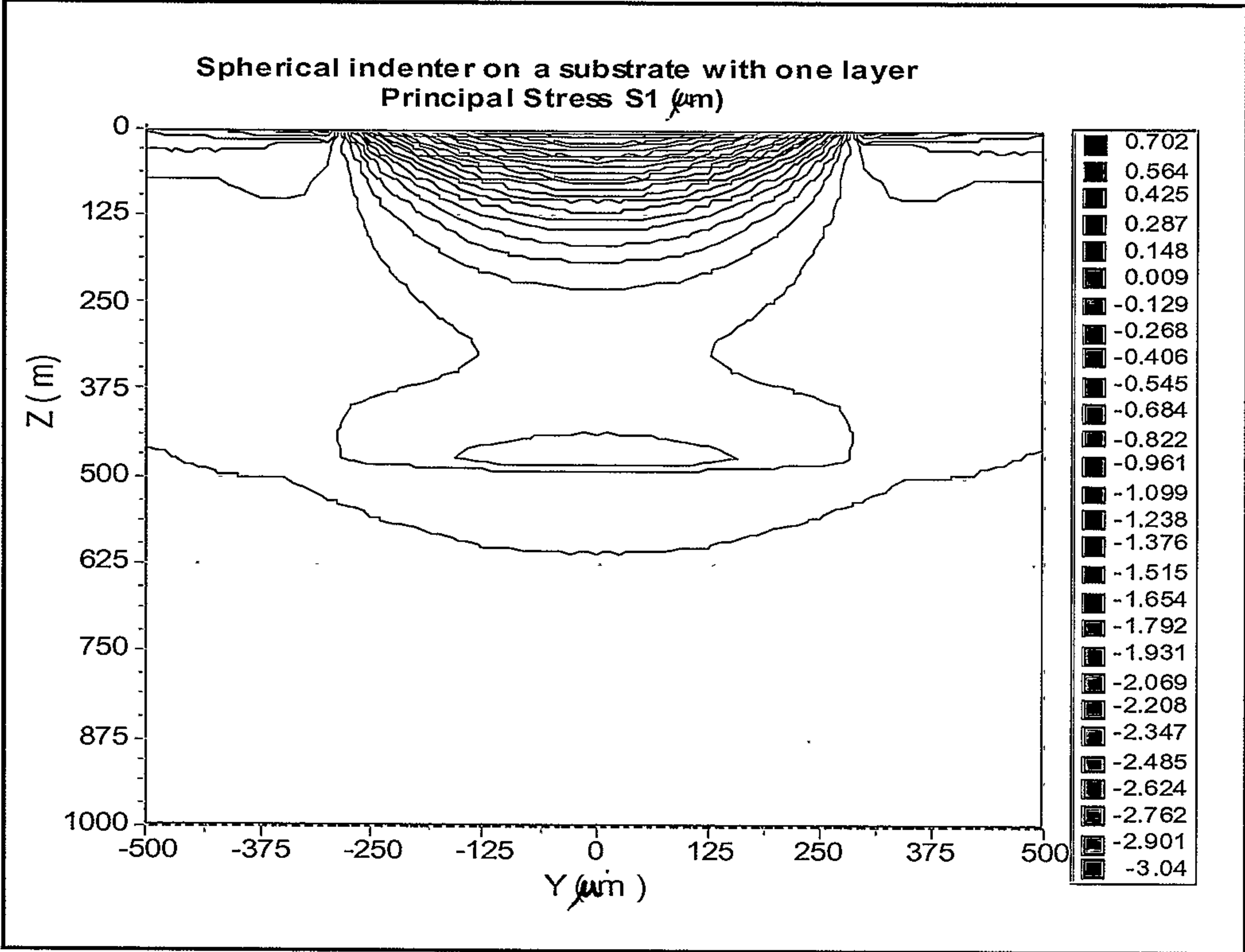


Figure 5.32 Stress distribution for 0.5 mm Vitadur Alpha on 1 mm In-Ceram. ($P = 845.8 \text{ N}$; Contact radius, $285 \mu\text{m}$)

The figure above (5.32) provides a diagram of the calculated stress distribution for the 5 mm ball indenter on the top surface of a bilaminar disc that has 0.5 mm Vitadur Alpha as the veneer and 1 mm In-Ceram beneath. The disc model was also supported by steel. The contact conditions were the same as previously. This contact stress is more than the one seen in figure 5.29. The average load at fracture was 845.8 N. The program also calculated the contact radius, which for this condition was $285 \mu\text{m}$. This is slightly greater than the previous condition. At the edges of the contact circle, the stress undergoes a steep change from compressive to tensile as would be expected for a Hertzian contact condition. This change for the x -axis has been plotted in figure 5.33 below. The maximum stress for this condition was 841 MPa and these results are again recorded in table 5.3.

The third figure for this condition (5.34) also demonstrates the stresses in the z – axis directly below the indenter. This plot has a gradient that also reflects the compression at the surface followed by a rapid reduction as the veneer is penetrated, the In-Ceram core again shows slight tensile stress which decreases as the interface is approached. This condition confirms the high damage level that occurs in the veneer layer beneath the indenter during testing. The region below the contact also suffers severe crushing.

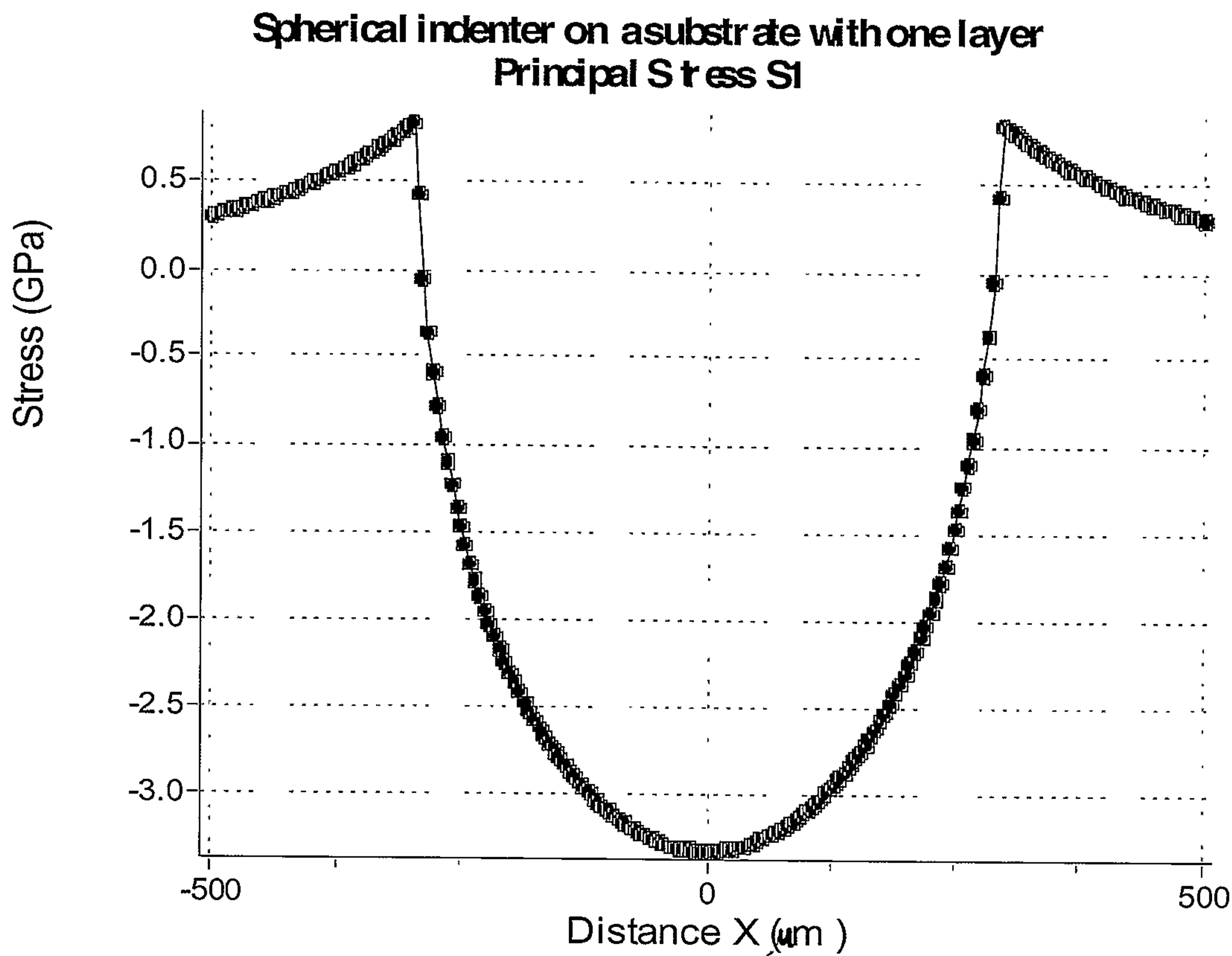


Figure 5.33 Principal stress distribution for 0.5 mm Vitadur Alpha on 1 mm In-Ceram in the X-axis.

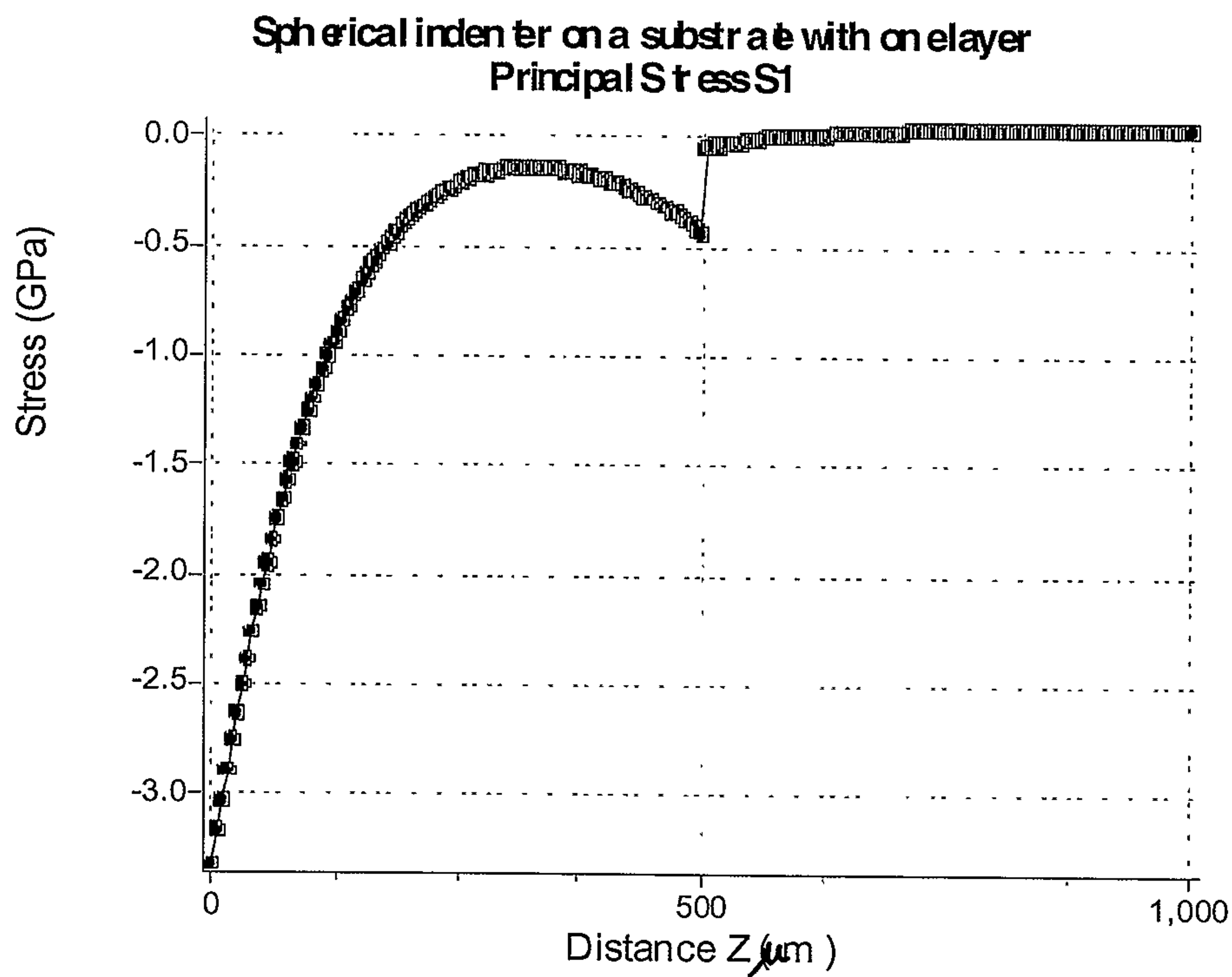


Figure 5.34 Principal stress distribution for 0.5 mm Vitadur Alpha on 1 mm In-Ceram in the Z-axis.

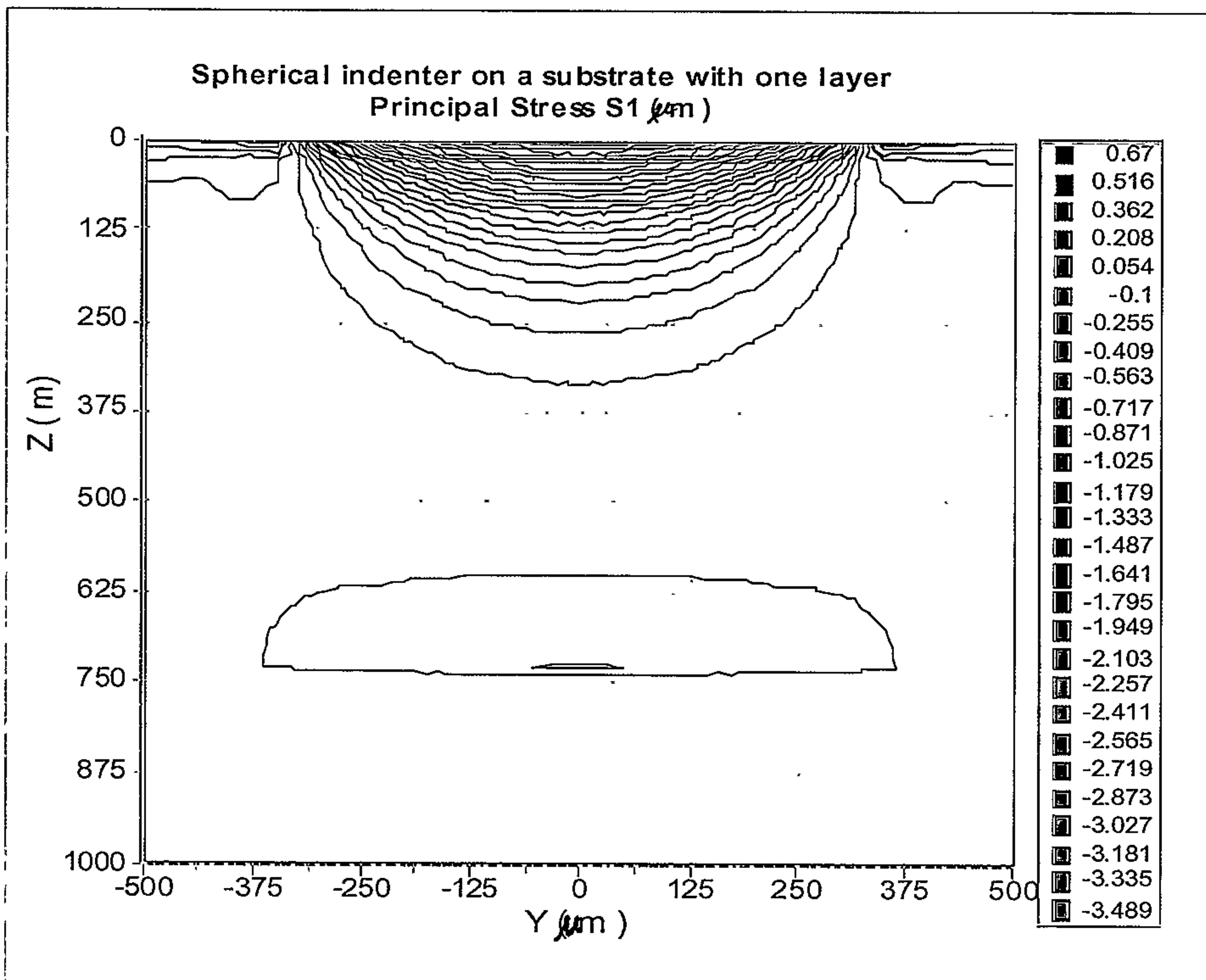


Figure 5.35 Stress distribution for 0.75 mm Vitadur Alpha on 1 mm In-Ceram. (P = 1188 N; Contact radius, 333 μm)

The figure above (5.35) provides the final stress distribution diagram in this series for the calculated stress distribution for the 5 mm ball indenter on the top surface of a bilaminar disc that has 0.75 mm Vitadur Alpha as the veneer and 1 mm In Ceram beneath. The disc model was also supported by steel. The contact conditions were the same as previously and the average load at fracture was 1188 N. The contact stress is greater than the ones seen in figures 5.29 and 5.32. The program also calculated the contact radius, which for this condition was 333 μm . This is greater again than the two previous conditions because of the higher load to cause failure. At the edges of the contact circle, the stress undergoes a steep change from compressive to tensile as would be expected for a Hertzian contact condition but it is less than the two previous cases. This change for the x -axis has been plotted in figure 5.36 below. The maximum stress for this condition was 824 MPa and these results are also recorded in table 5.3.

The third figure for this condition (5.34) also demonstrates the stresses in the z – axis directly below the indenter. This plot has a gradient that also reflects the compression at the surface followed by a rapid reduction as the veneer is penetrated, but with a return to an almost negligible compression compared with figure 5.31, as the interface is approached.

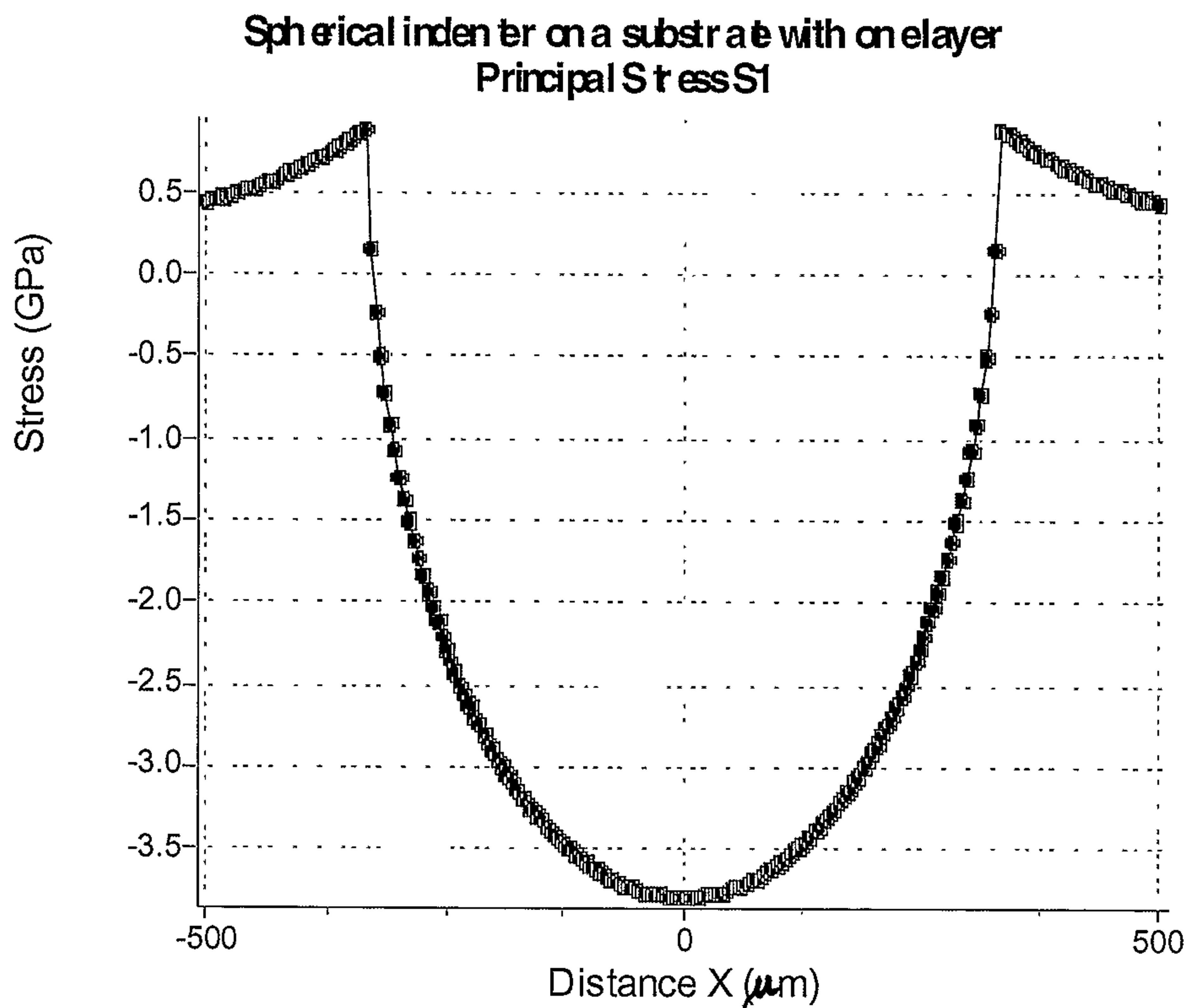


Figure 5.36 Principal stress distribution for 0.75 mm Vitadur Alpha on 1 mm In-Ceram in the X-axis.

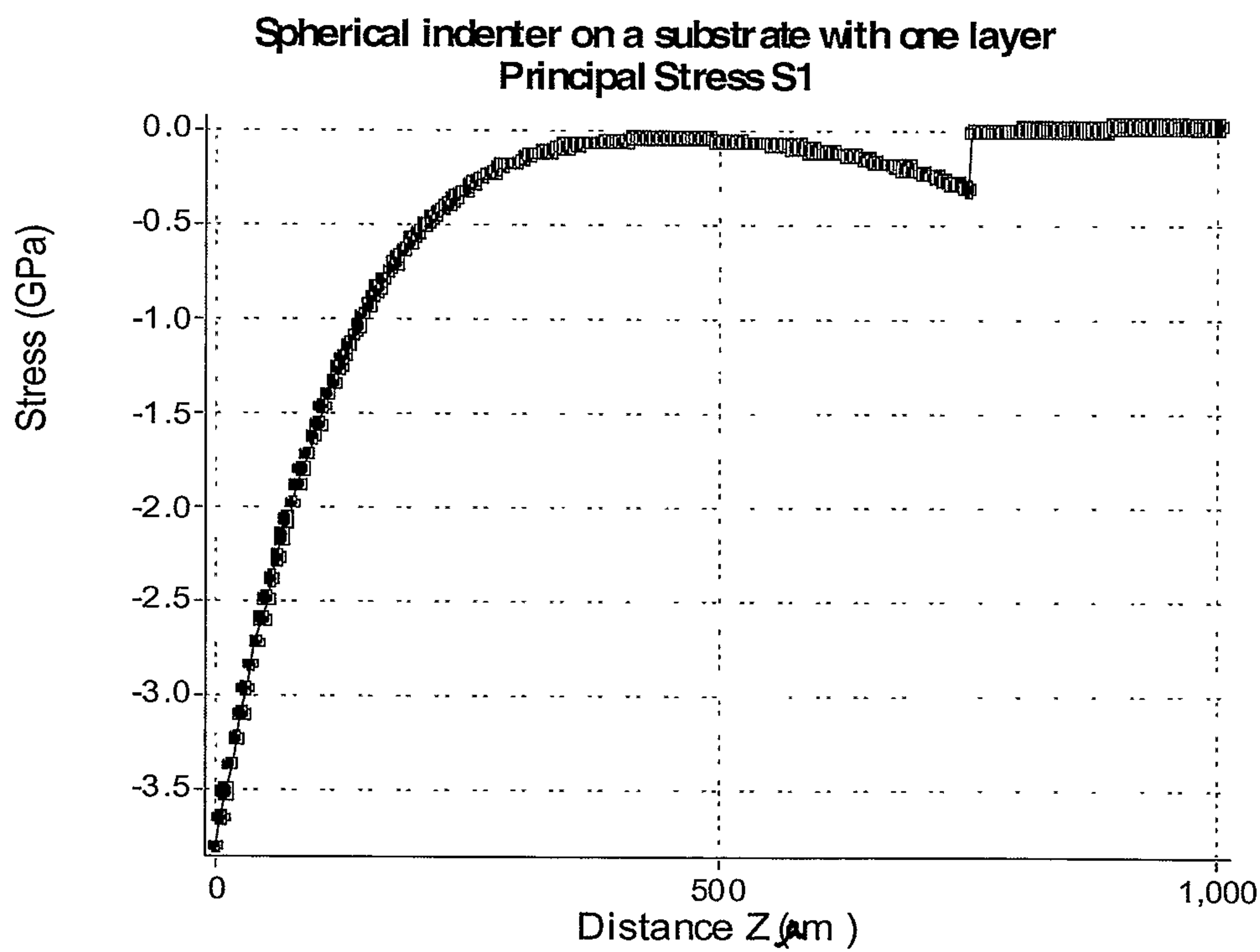


Figure 5.37 Principal stress distribution for 0.75 mm Vitadur Alpha on 1 mm In-Ceram in the Z-axis.

5.4 Discussion.

The object of this chapter was to find evidence that particular variations in the bilaminar construction could influence the initial fracture of the system. The system was tested in a supported mode because this is what normally occurs in the clinical situation. The analogue results where the discs were tested against a steel base indicate that high loads are required to fracture a completely In-Ceram specimen and that the loads for fracture progressively fall as the system is changed to one made completely from the porcelain, Vitadur Alpha. In all cases the supported discs were able to withstand higher loads than those tested without support.

The Finite Element Analysis indicates that the tensile stress on the lower surface of the In-Ceram is low and therefore not a major source of fracture. The results from the FEA also show that the tensile stresses developed on the bottom surfaces become lower as the support beneath the In-Ceram becomes stiffer. Conversely the results show that the tensile stresses at this surface increase as the In-Ceram thickness is decreased whilst the overall thickness is maintained. When the two factors, i.e. support stiffness and In-Ceram thickness are combined, the effects can multiply. The situation can become very disadvantageous for the overall system if the In-Ceram is thin and the support has a low elastic modulus.

The results from the analytical program, "Elastica", indicate that the surface tensile stresses are sufficient to cause cone crack initiation. This is in keeping with the results from chapter 3. The other information from this analysis was that the compressive stresses below the indenter were quite high, particularly for the thinner porcelain films. The system could then be open to crushing below the contact prior to overall system failure if the In-Ceram layer was either thick enough to handle the load or the support was stiff enough to assist the In-Ceram, or both situations applied.

From the results the trend appears to favour fracture resistance to be more dependent on core thickness than veneer thickness. Where the core thickness was kept the same, and the veneer thickness increased, the load applied to cause the initial failure also increased. However where the overall thickness was kept constant, but the ratio between the two layers varied, the results favoured the increased core thickness to produce an increased resistance to fracture. One outcome seems to be that although the cone crack appears first, the core holds the specimen together until the tensile stress on the undersurface exceeds the critical stress limit and the disc fractures. Clinically this might mean that a thick core could resist fracture under normal clinical loads, but if the veneer porcelain is not supported by the core, at the point of impact, it will fail. This failure can be quite independent of the core but nevertheless still constitutes a failure for the patient.

When considering the nature of the cone crack and its propagation towards the interface, it was clearly evident from the physical models that the premise that elasticity did not prevail throughout the indentation cycle was correct. Crushing of the veneer layer was common with some examples experiencing delamination and others developed radial cracks and complete failure. This highlights the comments of Davis et. al., (1991) where the model developed multiple variations of the basic crack processes available. The overall result was still the same, the disc failed, however this highlights the complexity of dealing with two non-homogenous materials with vastly different mechanical properties. Figure 5.38 below is a series of photographs highlighting this result.

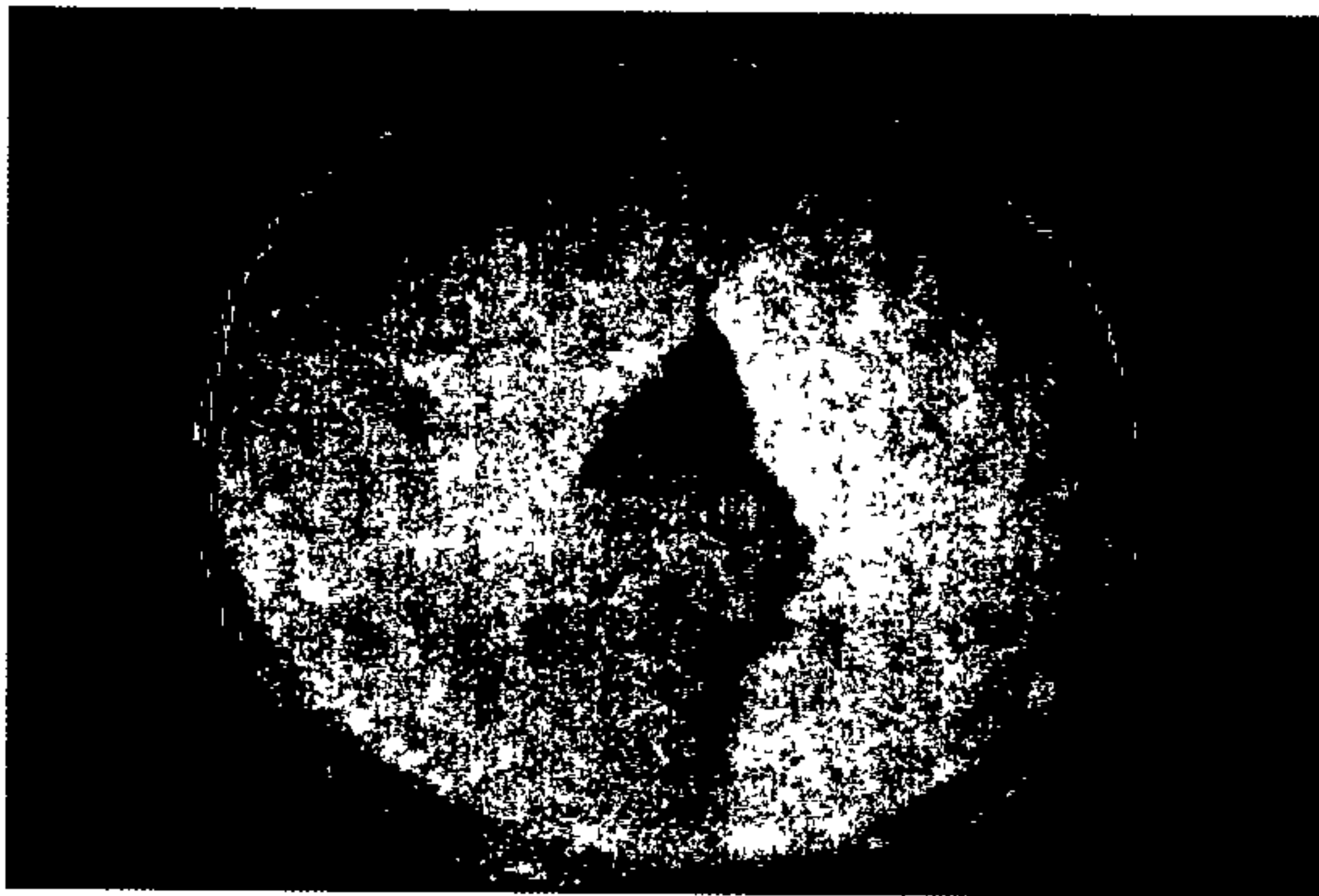


Figure 5.38a

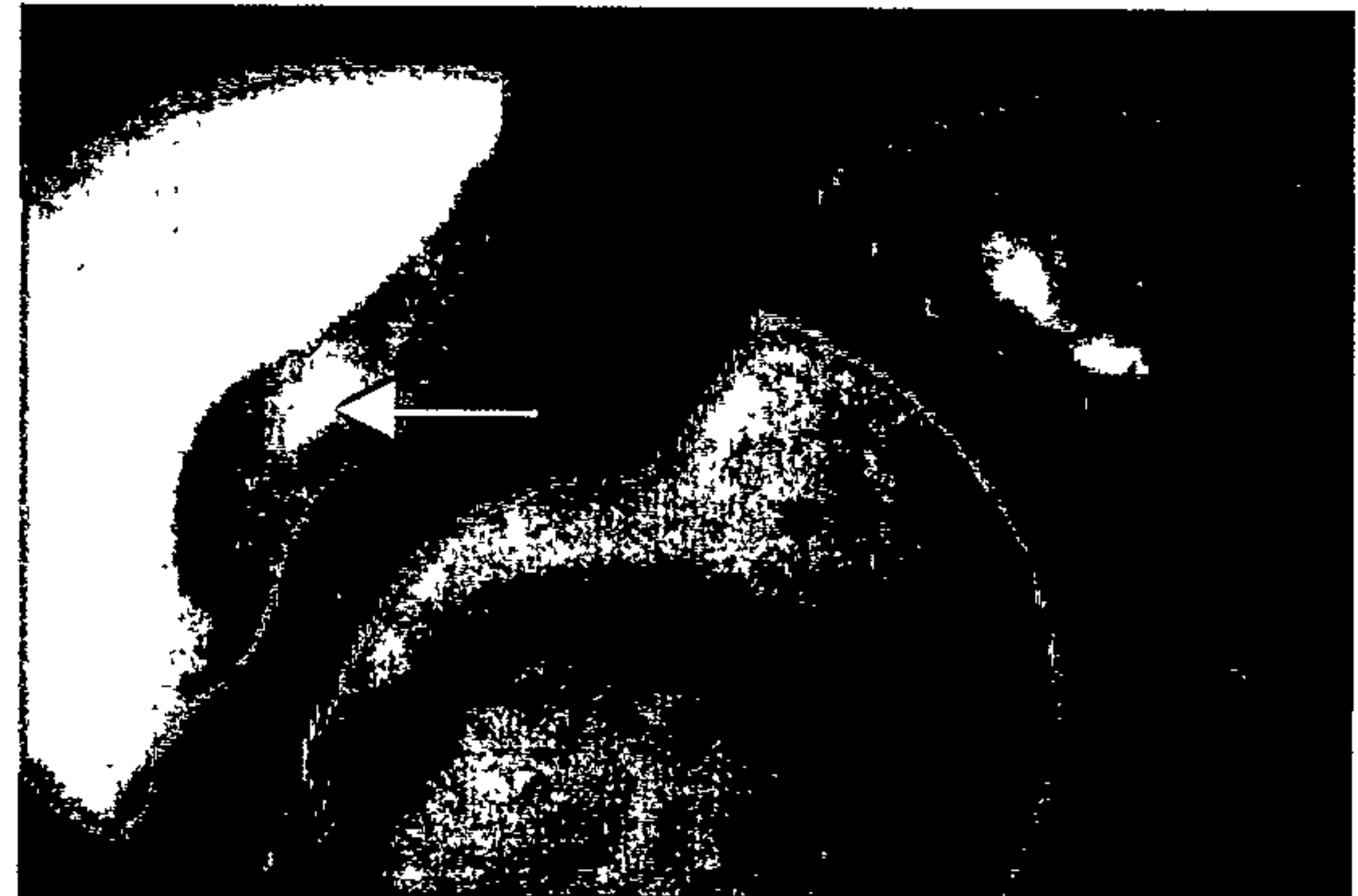


Figure 5.38b

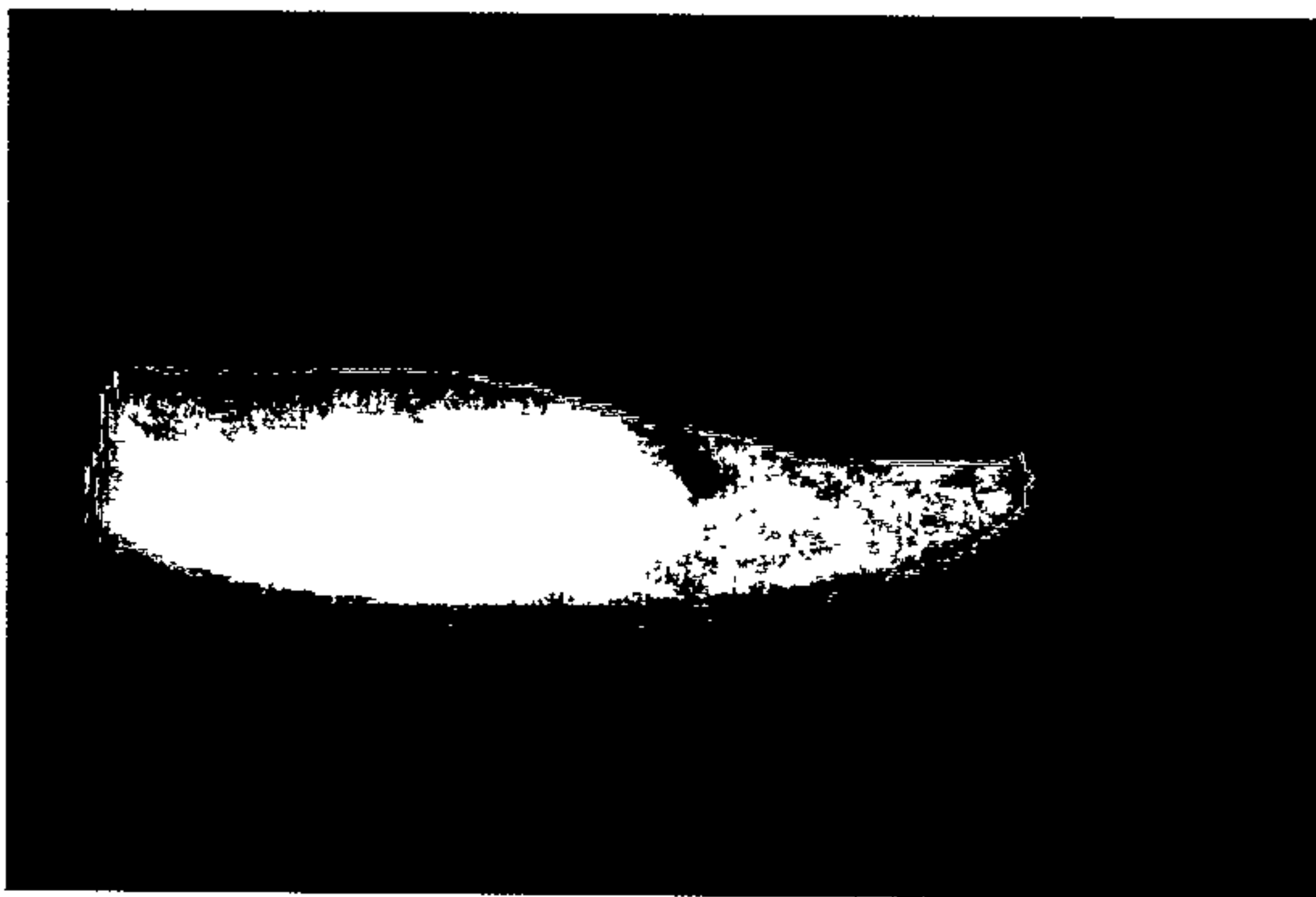


Figure 5.38c

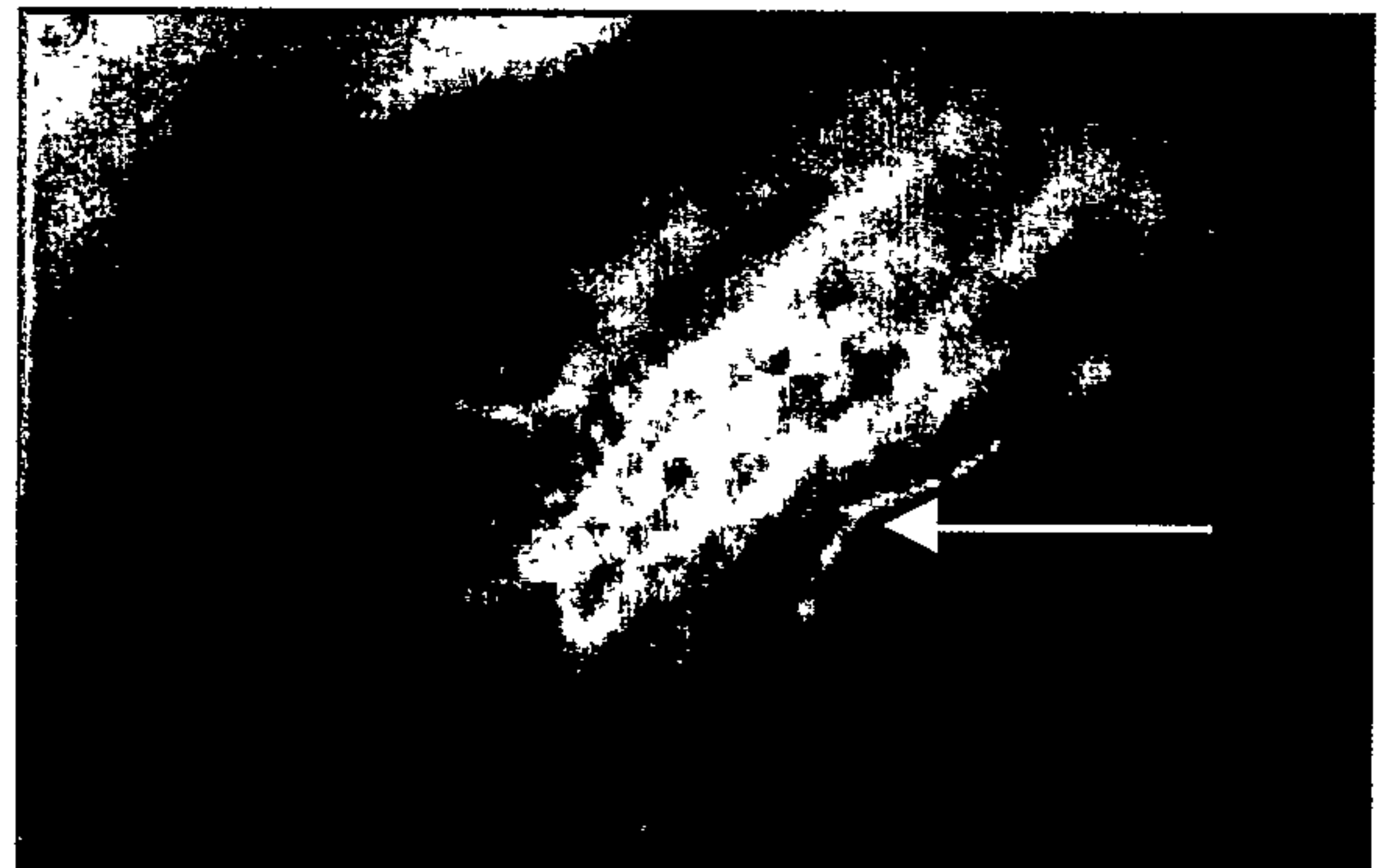


Figure 5.38d

Figure 5.38 (a) Demonstrates the top view of the three remaining parts of the disc after loading. The contact region has completely failed and the crushed particles are missing. (b) Demonstrates the three major parts: the left shows the undersurface, the centre is the top view and the right part is also the undersurface. (c) Demonstrates the form of the cone crack and the delamination. (d) Demonstrates the area of the Vitadur Alpha adjacent to the intersection of the cone crack and the delamination - strong hysteresis of the Vitadur Alpha occurred at this point.

Although not physically tested finite element models were developed for designs where the veneer layer thickness remained constant at 1 mm, but the core layer was reduced to 0.75 mm, 0.5 mm, and 0.25 mm respectively. These were tested for both the flat base and the three ball support modes. These models in conjunction with the analytical modeling using "Elastica" have confirmed the tempering nature of the increased depth of the Vitadur Alpha porcelain to contact stresses. The tempering reduces the compressive stress on the In-Ceram, seen at the interface between the two layers. Data from the "Elastica" plots indicates that very high stresses appear on the top surface when the veneering ceramic is supported by a stiff base. For a constant In-Ceram thickness, as the Vitadur Alpha is reduced in thickness, the contact radius and the stress gradient from the centre to edge of the contact circle reduces. The compressive stress at the interface with the In-Ceram increases.

Both the FEA and the analytical modelling confirm the influence of the support layer as a major contributor to the development of stress at particular surfaces.

The thickness of the core layer also influences stress development and load bearing capacity. When the 5 mm ball indenter was applied to the discs as they were supported on the steel base, an expected reduction in the load to fracture occurred as the core was reduced and the veneer increased; the overall thickness remained the same. From figure 5.5 and table 5.5 it can be seen that the disc with the thinnest core layer developed the highest radial (tensile) stress on the bottom surface. As the support modulus increased to that of dentine the tensile stress decreased and finally as the modulus was increased to that of steel, the radial stress on the bottom surface decreased even further. So there are two major factors affecting the development of radial stress on the bottom surface; one is the stiffness of the support and the other is the thickness of the core.

5.5 Conclusions.

Although significant stress gradients occur at the interface they are not the most likely origin of fracture.

When the support layer has a higher modulus of elasticity than the veneer porcelain, with values closer to the core ceramic layer, the stresses developed on the underside of the core layer are insufficient to fracture the core ceramic at normal occlusal loads.

Where the veneer porcelain is thicker there is sufficient strain (deformation) to create high enough tensile stress just outside the contact area to initiate a fracture. The principal tensile stresses for groups were all sufficient to fracture the veneering porcelain.

The design of crowns needs to consider the support base for the core ceramic and the core ceramic layer needs to be as thick as possible.

Application of the design to Crowns

6.1 Introduction

The resistance to crack initiation from a spherical indenter has been examined and will be applied to the design of anterior crowns to be tested in vitro. This chapter is designed to confirm that the findings from previous chapters can be applied to In-Ceram® crown design and produce a more crack resistant structure.

The three main areas of interest for crack initiation in these crowns are:

1. The outer surface of the Vitadur Alpha veneer layer.
2. The inner surface where the In-Ceram meets the core of the tooth via a luting agent.
3. The interface between the Vitadur Alpha and the In-Ceram.

The outer surface has been shown from the limited clinical results and the in vitro testing in chapter 3 to be subject to cone crack formation when it is normally loaded and supported by either dentine or metal cores. This tendency has been confirmed by the Elastica contact mechanics stress analysis in chapter 5. The cone crack extensions for the crown designed according to the manufacturer's instructions did not appear to be the ultimate cause for failure of the core, but they did lead to delaminations of the veneer layer when the interface was reached. The mechanics of crack propagation at the interface was discussed in section 2.5.4 where it is clear that the changes in structure caused by the formation of new crack surfaces along the interface of different materials can add to the driving forces to propagate the delamination. The observation of the failed crowns in chapter 3 also indicated the probable formation of median and radial cracks that led to the final failure of the crowns.

The test model for crowns in chapter 3 was deliberately designed to have the load applied over the core on the palatal surface. The reason was because it allowed the design of a simple bilaminar disc to study the fracture processes further, and the palatal area could be reinforced with more core material at little or no expense to aesthetics. Many anterior metal-ceramic crowns are made with metal palatal surfaces, which are not visible. In the

following chapter the ceramic system was studied using the ISO standard for dental ceramic. This began the investigation for the behaviour of the bilaminate system under flexural conditions. The biaxial test for the ISO standard tests the ceramic in a mode where the area below the specimen, opposite to the application of load is unsupported. This test provided information about how the two individual ceramic materials behaved under flexure and gave a value for their flexural strengths. Variations of the thicknesses of the two components provided additional information about how to improve the load bearing capacity. The next series of tests outlined in chapter 5, involved loading different bilaminate discs while they were supported. The object was to see if this improved their resistance to fracture and what combinations of support and ceramic core to porcelain veneer thickness ratios were useful to improve fracture resistance. The outcome of this chapter suggests possibly two designs, one based on the ability of Vitadur Alpha to temper the load when it has some thickness and the other based on the inherent strength and stiffness of In-Ceram to resist fracture initiation.

The question of support for these designs from the core preparation is not an issue because it is the design itself that is being investigated. The tests are simply to review the resistance to fracture between the two designs, based on their ceramic construction.

This chapter will explore two designs based on the information gained. The first will test crowns where the palatal surface is reinforced by a ceramic collar which has the same dimensions and form that could be found with most of the common anterior metal-ceramic crowns made in clinical practice. The second design will test crowns that have the palatal surface made almost entirely with In-Ceram core material. The In-Ceram will be coated with a thin layer of Vitadur Alpha or with a thickness range approximating 0.25 mm or less. The manufacturer's instructions require the In-Ceram to be sealed with Vitadur Alpha to prevent corrosion of the lanthana based infiltration glass.

6.2 Materials and Methods.

Two groups of anterior crowns were constructed according to the following designs, (figures 6.1 and 6.2) (Ironsides 1993). The construction and firing schedules are listed in Appendix II, which is according to the manufacturer's instructions. The first group were designed with a palatal collar (Collared Design, n=25) and the second group had an In-Ceram® palatal with a thin layer of Vitadur Alpha® (Backed Design, n=24). All crowns were finished with a high glaze (Vitachrom Delta® 740). The construction method was the same as that used in chapter 3, the only difference being the design. The overall dimensions were guided by silicone rubber profiles.

The specimen crowns were cemented to sandblasted brass dies that were mounted in a universal testing machine, with the palatal surface at right angles to the loading axis, with the load point mid way between the incisal edge and the palatal gingival margin, (see figures 6.3 and 6.4). These crowns were then tested according to the protocol described in chapter 3 using a universal testing machine.

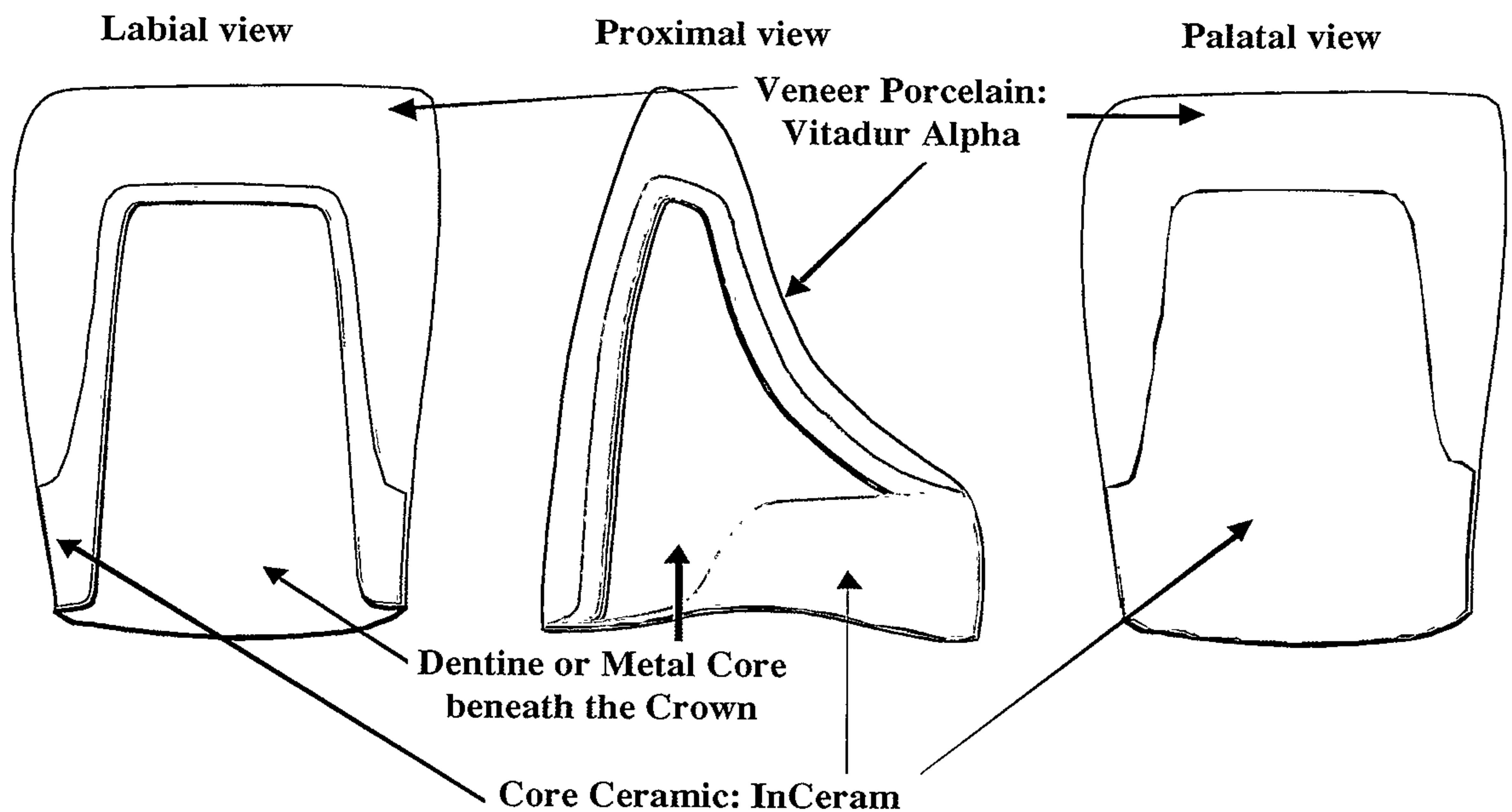


Figure 6.1. The collared core design.

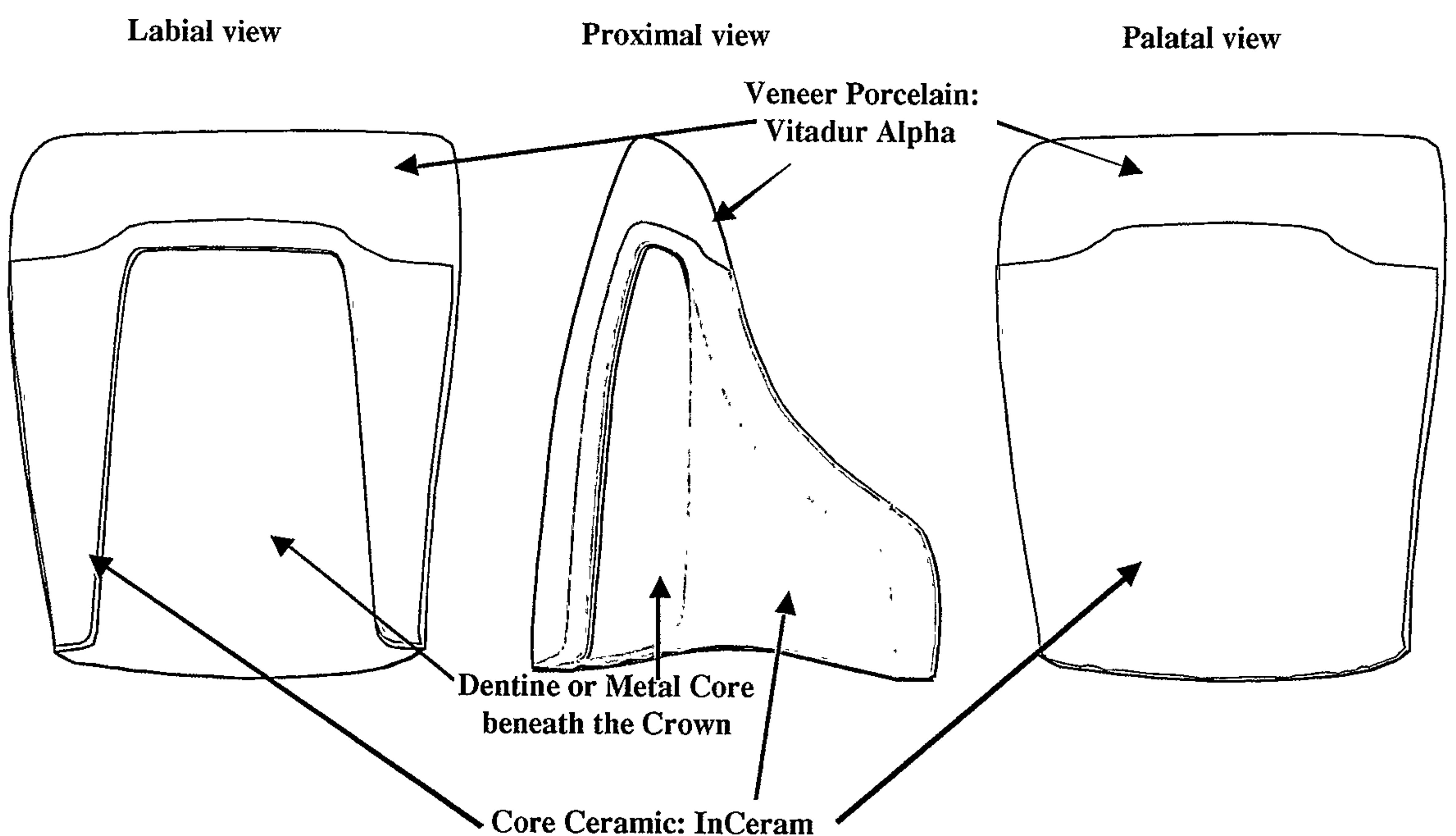


Figure 6.2. The backed core design.

A 5 mm spherical indenter was used at a crosshead speed of 0.5 mm per minute to initiate the crack. Crack initiation was determined from the continuous plot on the recording chart

from the testing machine. The initial crack formation left a step in the recording trace and was accompanied by an audible click. An example of the step appears in figure 3.16. The initial cracks were photographed by photomicroscopy. The fracture patterns were also categorized according to their form, in the same manner that was used in chapter 3. After the crowns were removed from the dies their relative layer thicknesses were measured and recorded.

Diagrams for the loading of these crowns appear in figures 6.3 and 6.4.

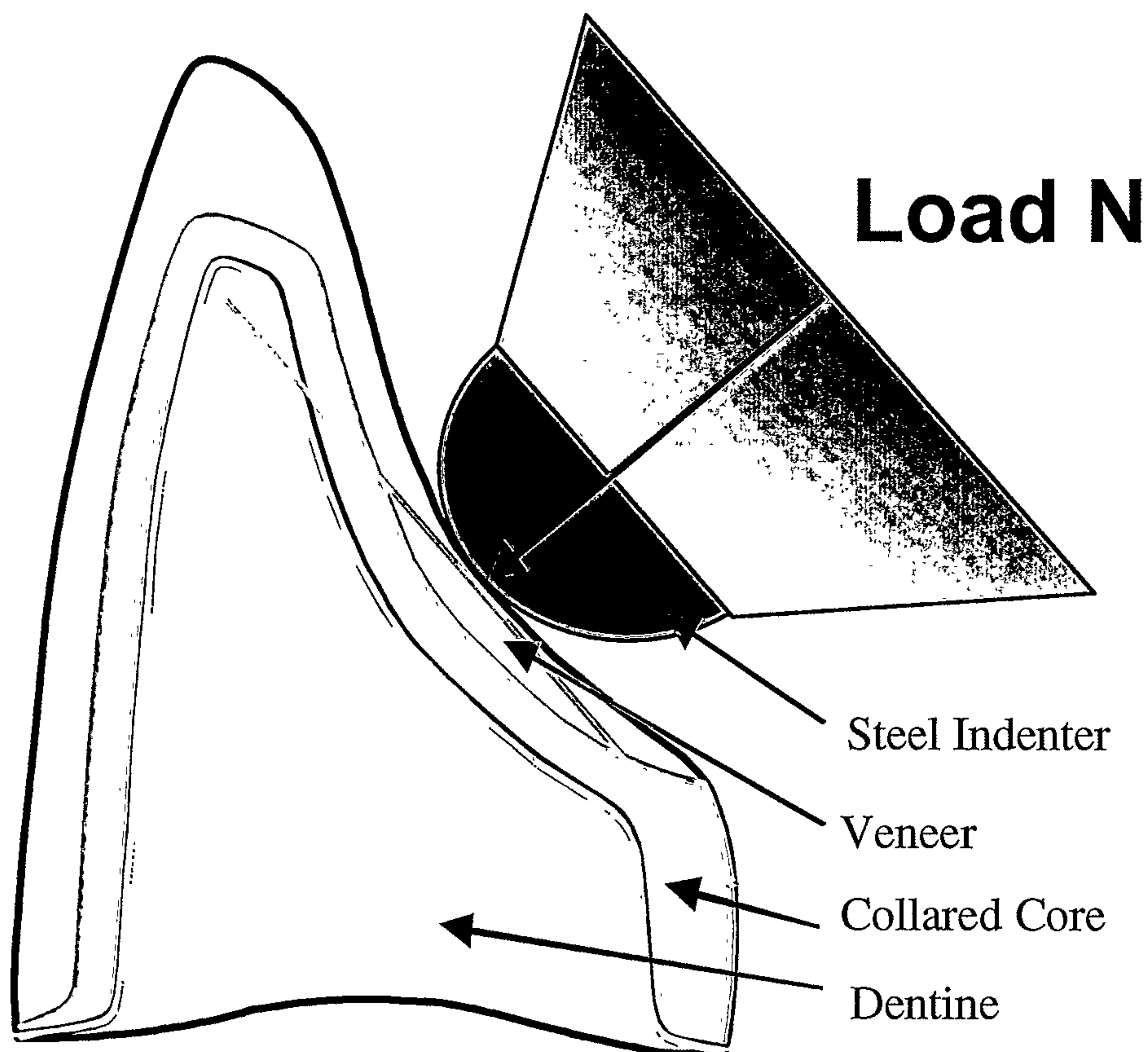


Figure 6.3. Diagram of direction of the load application to the in vitro collared crown. The load (red arrow) was aligned at right angles to the plane (green line) of the palatal surface at the contact point.

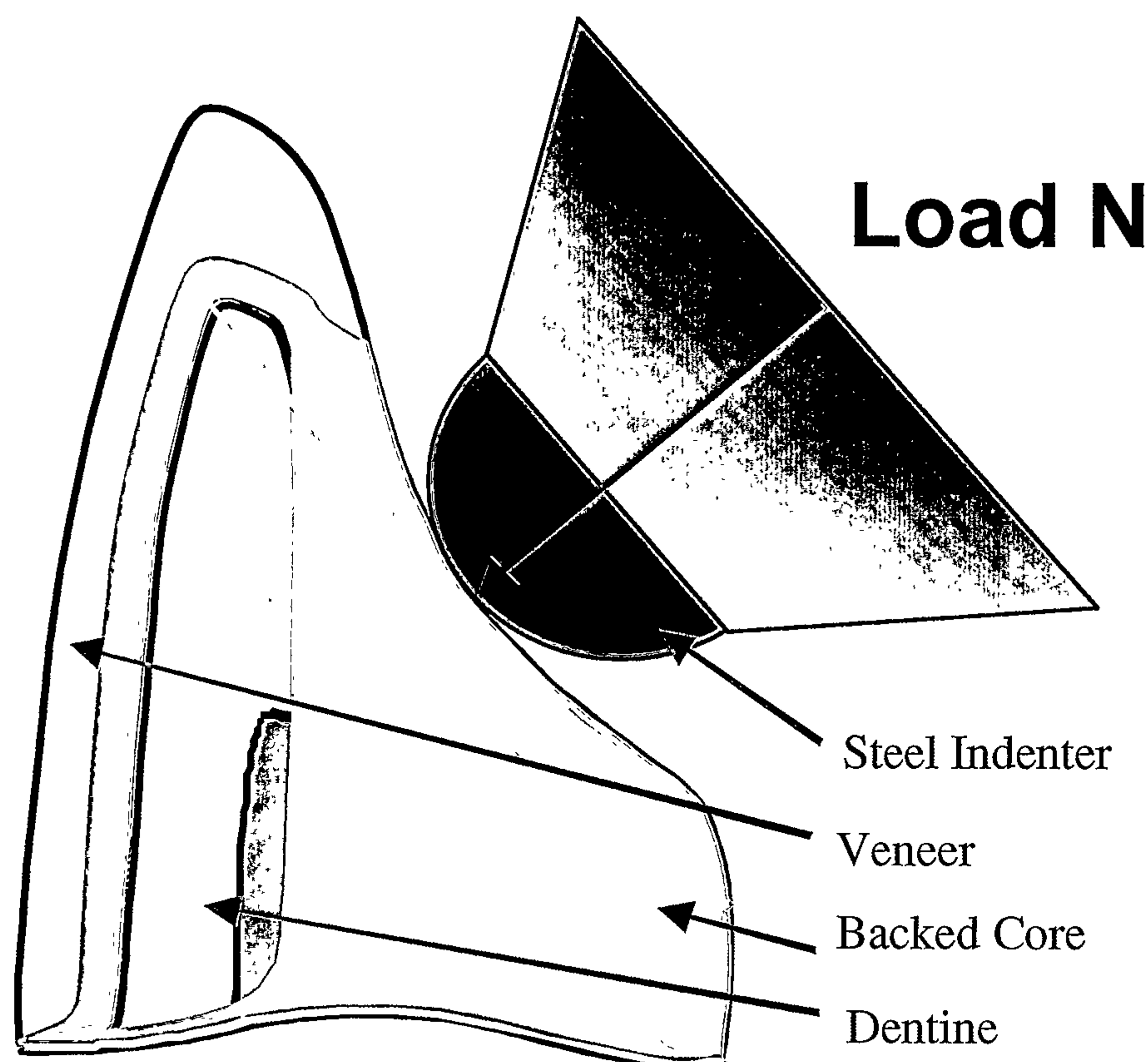


Figure 6.4. Diagram of direction of the load application to the in vitro collared crown. The load (red arrow) was aligned at right angles to the plane (green line) of the palatal surface at the contact point.

The fractured crowns were individually assessed for the type of fracture, i.e. did they appear to follow a more traditional fracture pattern, (as typified by a Hertzian cone crack in glass) or did they demonstrate a fracture pattern consistent with a crush injury to the outer surface followed by extension of the fracture process through the crown towards either the inner surface, or another part of the crown which would have resulted in a clinical failure. The fractured crowns were photographed under reflected light microscopy and graded according to the style of crack as discussed in chapter 3. The core thicknesses were also measured and recorded. Examples of the fracture patterns appear below in figures 6.5 and 6.6. Figures 3.17 a & b provide palatal views for these types of fractures.

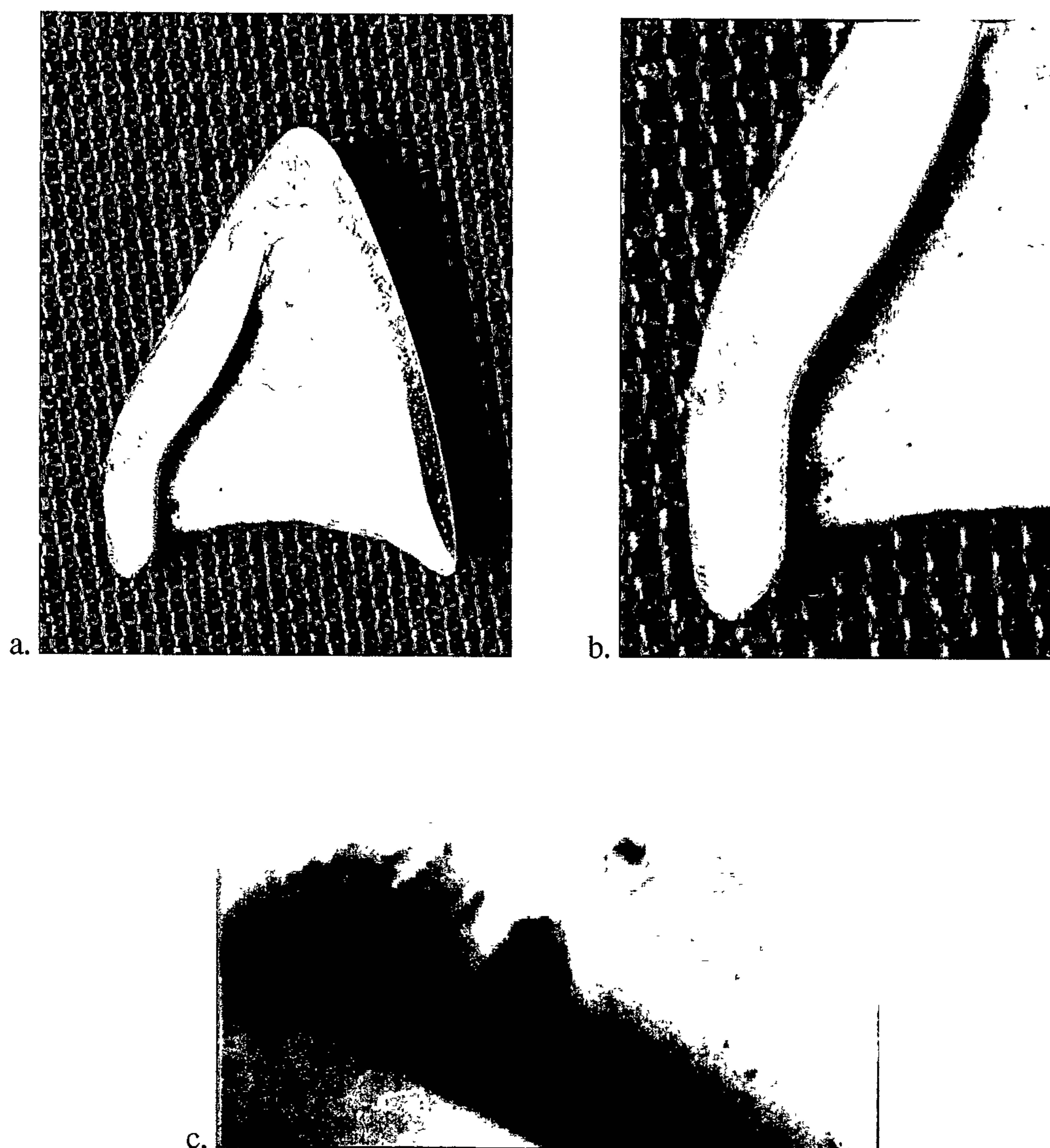


Figure 6.5 Type I fracture pattern on a crown from the Collared core design

The photographs in figure 6.5 show a cone crack fracture at the centre of the palatal surface. In figure 6.5a the overall picture is not dissimilar to figure 3.18. A closer view is seen in figure 6.5b. However figure 6.5c is a close-up of the fracture from specimen C2 and although the classic lines of cone cracks can be seen, there is also evidence that the porcelain was crushed.

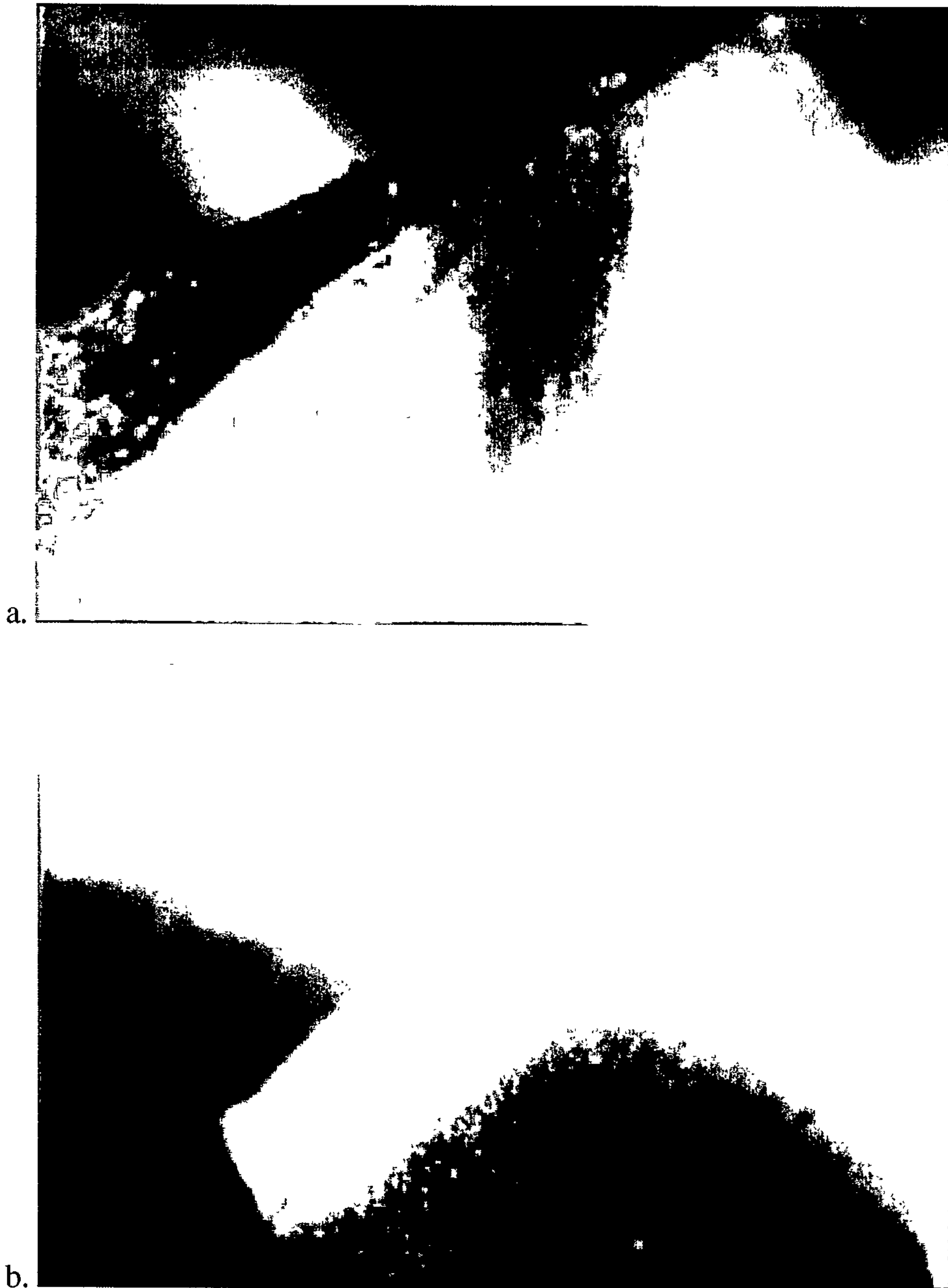


Figure 6.6 Type II fracture pattern on a crown from the Backed core design

The photographs in figure 6.6 demonstrate the damage that arose from the specimens with the backed core design. Figure 6.6a is from specimen B52. The surface of this specimen shows evidence of crushing and the other crack lines indicate cone crack and radial crack formation. The veneer thickness for this specimen was 0.31 mm and the failure load was 1488 N. Figure 6.6b is from specimen B69. This specimen failed at 2024 N, the highest of all the crowns. The veneer layer was extremely thin at 0.1 mm. There is evidence that this crown suffered crush damage on the surface, followed by radial and cone cracks. Both cases reveal a far more complex damage pattern than a simple cone crack followed by radial cracking.

6.3 Results.

6.3.1 Mechanical Test Results.

The results from the universal testing machine are listed in Tables 6.1 and 6.4 for the collared and backed designs respectively. The loading system again provided support below the contact area in a manner not dissimilar to the supported bilaminate discs.

As described in chapter 3, the mean crack initiation loads for Non-collared crowns was 1096 N. In this latter experiment, the mean crack initiation load for Collared crowns, was 1185.2 N; and for Backed crowns, the load was 1498.8 N. The results are analysed using conventional statistics and Weibull statistics because they have wide variations. The use of scattergrams has been employed to demonstrate the non-uniformity that is associated with hand made crowns. Variations in the layer thicknesses do not produce changes to the loads for fracture initiation on a strictly linear basis. The type of crack pattern seen in the crowns with the heavier In-Ceram content in the palatal surface has tended to be the second type. This observation would lend weight to the argument that increasing the core thickness at the expense of the veneer thickness will create a condition requiring higher loads for fracture initiation. The other aspect is that the second type of crack appears to start with a cone crack and area of crushing followed by delamination and eventually by radial cracks.

6.3.1.1 Results for the “collared” design crowns.

The results from the universal testing machine for the crowns designed with palatal collars are listed in table 6.1 below. The results include measurements of the load for the initial crack development and the load when the crown failed completely, i.e. the core ceramic also cracked. The table includes the core and veneer thicknesses for each crown. The layer thicknesses have wide variation, which could be expected from the construction protocol. The overall thicknesses are reasonably consistent.

Table 6.1 Results for the collared design crowns

	Spec ID	Initial Crack load (N)	Load at final failure (N)	Fracture Pattern	Core Thickness (mm)	Veneer Thickness (mm)
Mean	•	1185.200	1233.6		0.828	0.597
Std Dev.	•	237.785	230.7		0.159	0.159
1	C1	1020	1020	I	0.790	0.410
2	C2	1003	1003	I	0.890	0.490
3	C5	1781	1781	II	1.160	0.440
4	C6	1337	1449	II	0.950	0.580
5	C8	1266	1271	I	0.520	0.580
6	C9	1085	1216	I	1.120	0.410
7	C11	860	1358	I	0.740	0.740
8	C12	1330	1340	I	0.560	0.840
9	C13	1109	1246	I	0.680	0.700
10	C15	1105	1112	I	0.860	0.600
11	C17	1404	1411	I	0.930	0.750
12	C20	1492	1493	II	0.910	0.680
13	C24	1400	1441	II	1.000	0.460
14	C25	1198	1343	I	0.950	0.300
15	C26	1005	1005	II	0.850	0.700
16	C27	1151	1152	II	0.820	0.640
17	C28	1090	1090	II	0.580	1.000
18	C29	731	759	I	0.750	0.590
19	C30	1452	1453	II	0.830	0.740
20	C31	928	940	I	0.750	0.480
21	C32	841	841	I	0.810	0.430
22	C61	1406	1406	II	0.700	0.690
23	C62	1148	1204	II	0.880	0.540
24	C63	1324	1324	II	0.970	0.460
25	C64	1164	1181	II	0.700	0.680

The layer thicknesses for the collar design were measured and recorded in table 6.1. The average veneer thickness is almost identical to those from the first series of standard crowns in chapter 3. The average core thickness is slightly thicker at 0.828 mm compared with 0.613 mm for the standard crown group. The difference was probably caused by the design causing an effective flow of alumina slip to the outer contour of the collar and resulting in the slight increase in thickness. Statistically there is no significant difference in load to initial fracture and final failure although it is slightly higher. However, when the results for the collared crowns are split according to their fracture type, there are differences, which need to be addressed. The divided results are seen in table 6.2.

Table 6.2 **Mean results for the collared design crowns**

	Initial Failure Load (N)	Final Failure Load (N)	Core Dimen. (mm)	Veneer Dimen. (mm)	Overall Dimen. (mm)
Type I (n=13)	1068	1143	0.796	0.563	1.359
Type II (n=12)	1312	1331.6	0.862	0.634	1.496
Paired t-test	0.015	0.1221	0.273	0.1934	0.046

The results for this group were plotted in a series of scattergrams with regression lines to form a view of the trends. The scatter grams for initial failure loads were plotted according to fracture type, core and veneer thickness, and overall thickness.

Figures 6.7 and 6.8 display a seemingly random pattern until the regression lines are taken into account. In the scattergram in figure 6.7 the negative slope is for the core thickness, indicating that as the core becomes thinner, the initial fracture load increases. The positive slope is for the veneer thickness, which, as it becomes thicker, the load to initial fracture increases. This is contrary to the expected result, however when the overall thickness dimension is taken into account, the trend is for the load to increase with the thickness. This is displayed in figure 6.9.

The correlations between the fracture types, loads and layer thicknesses appear in table 6.3. In general the correlations are not very strong, however they have significance due to the large number of samples. For overall thickness there is a mild positive correlation, that is, the thicker the crown the higher the load. There is a slightly negative correlation for core thickness and type I fractures which may mean that other factors such as manufacturing defects were a more predominant part of their failure process. The core thickness for type II fractures had a strong correlation and the veneer thickness for this type had a negative correlation indicating that the thinner the veneer the higher a load that could be endured.

Table 6.3 Correlation values for Type I and II fractures for the “Collared” design crowns.

Initial failure load versus Overall dimension			
	Mean Failure (N)	Correlation Coef.	Fisher's R-Z
Type I (n=13)	1068	0.240	0.3049
Type II (n=12)	1312	0.327	0.3089

Initial failure load versus Core thickness			
Type I (n=13)	1068	- 0.062	0.8455
Type II (n=12)	1312	0.650	0.0200

Initial failure load versus Veneer thickness			
Type I (n=13)	1068	0.305	0.3199
Type II (n=12)	1312	- 0.476	0.1202

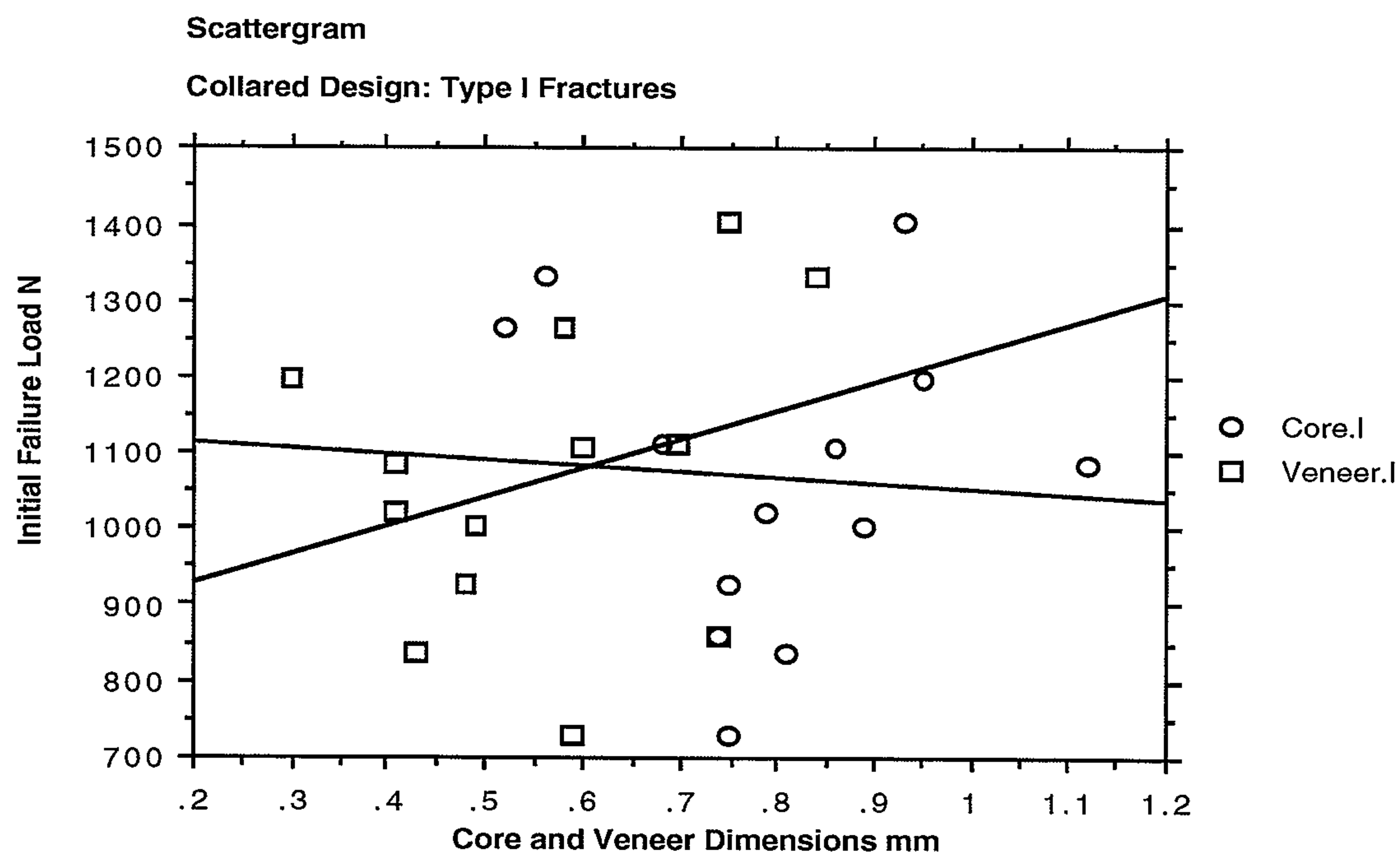


Figure 6.7 Scattergram for the type I results from the collared design group.

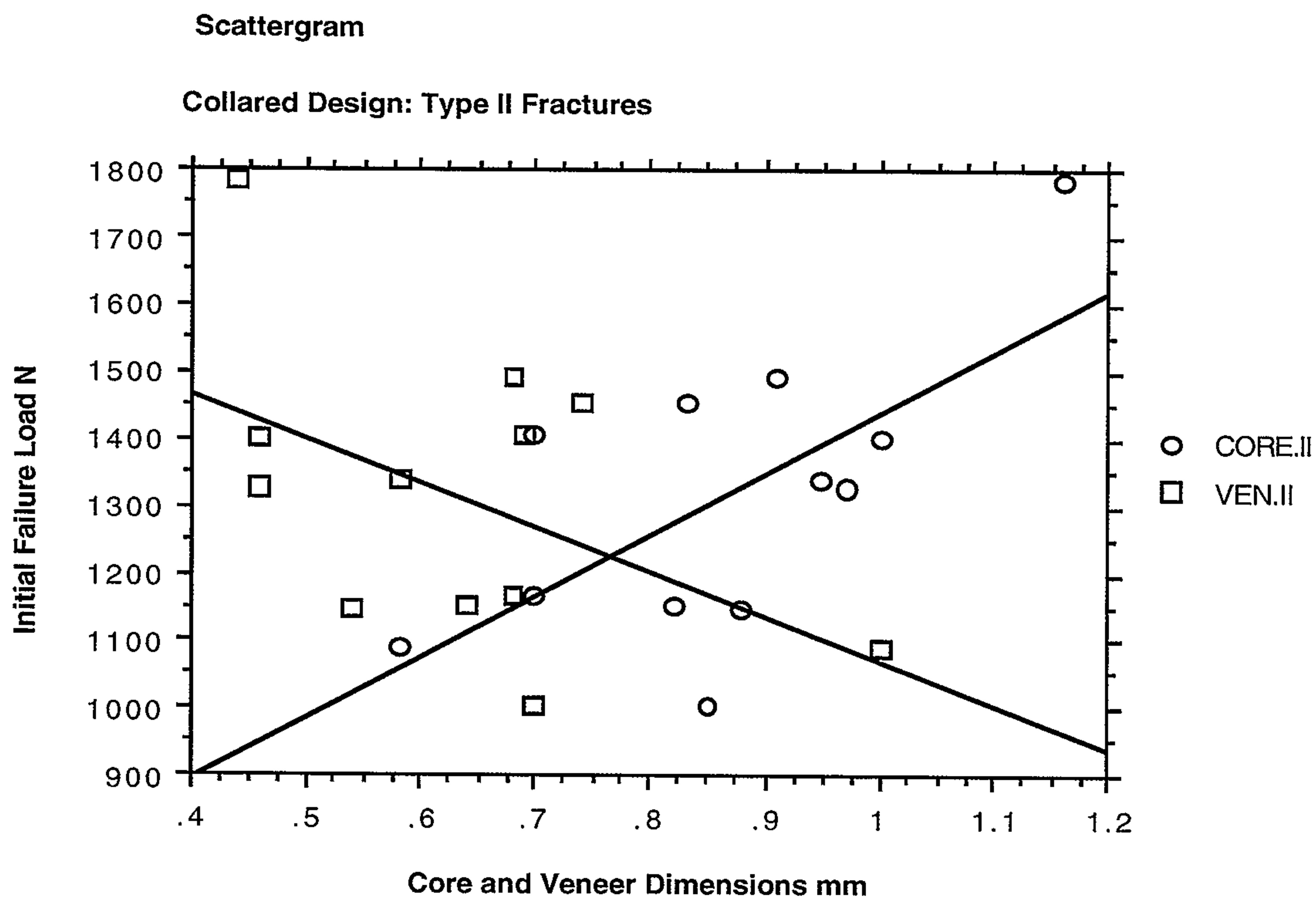


Figure 6.8 Scattergram for the type II results from the collared design group.

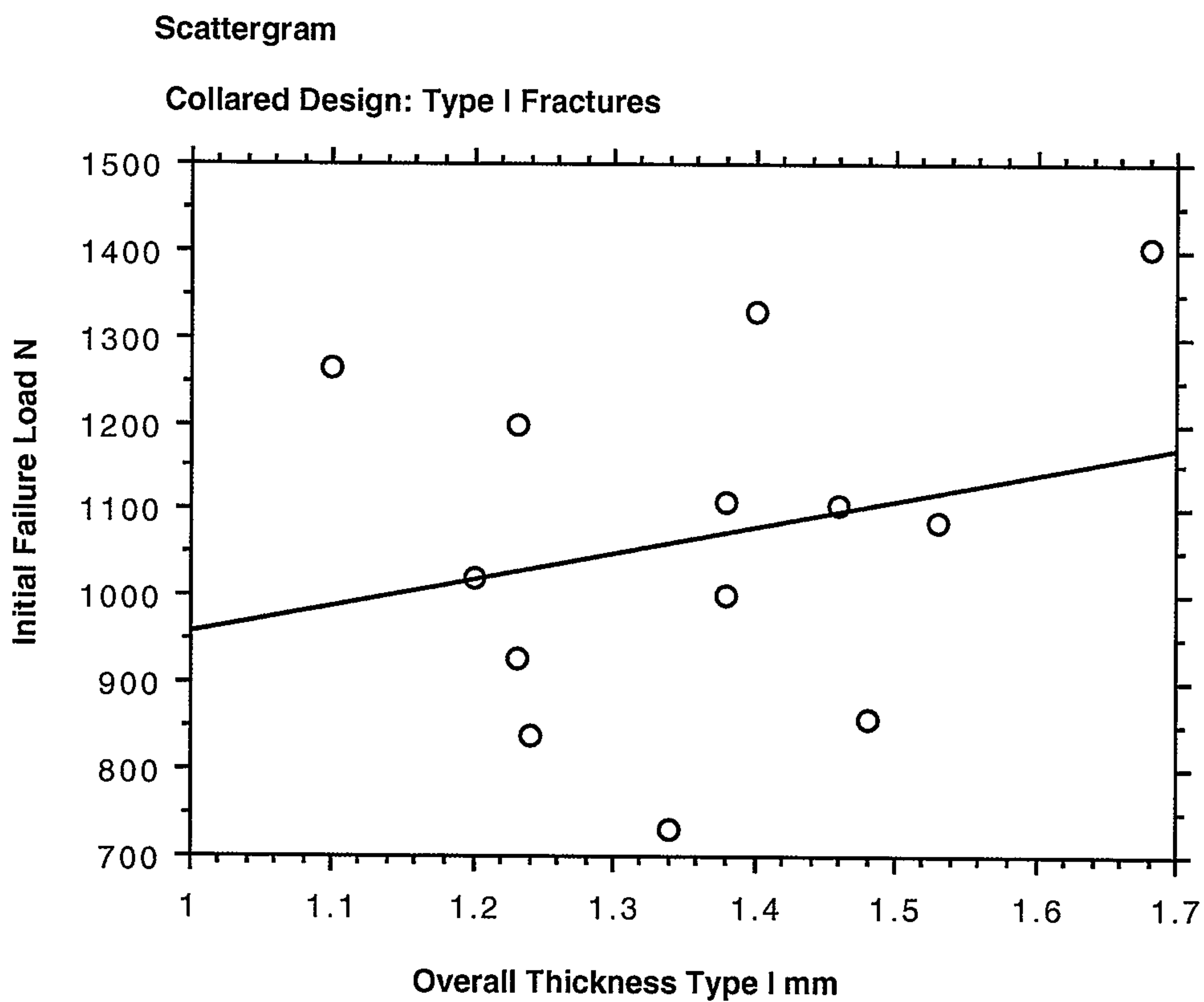


Figure 6.9 Scattergram for the type I results from the collared design group, comparing the initial failure load to the overall thickness dimension.

The result for the overall dimension for type I failures has a slight positive correlation between the thickness and the load. That is, the thicker the crown the higher the load. The core and veneer thicknesses are approximately the same and when different thickness bilaminate discs were tested for flexural strength, there was an increase in strength according to increase in thickness. This result would seem reasonable.

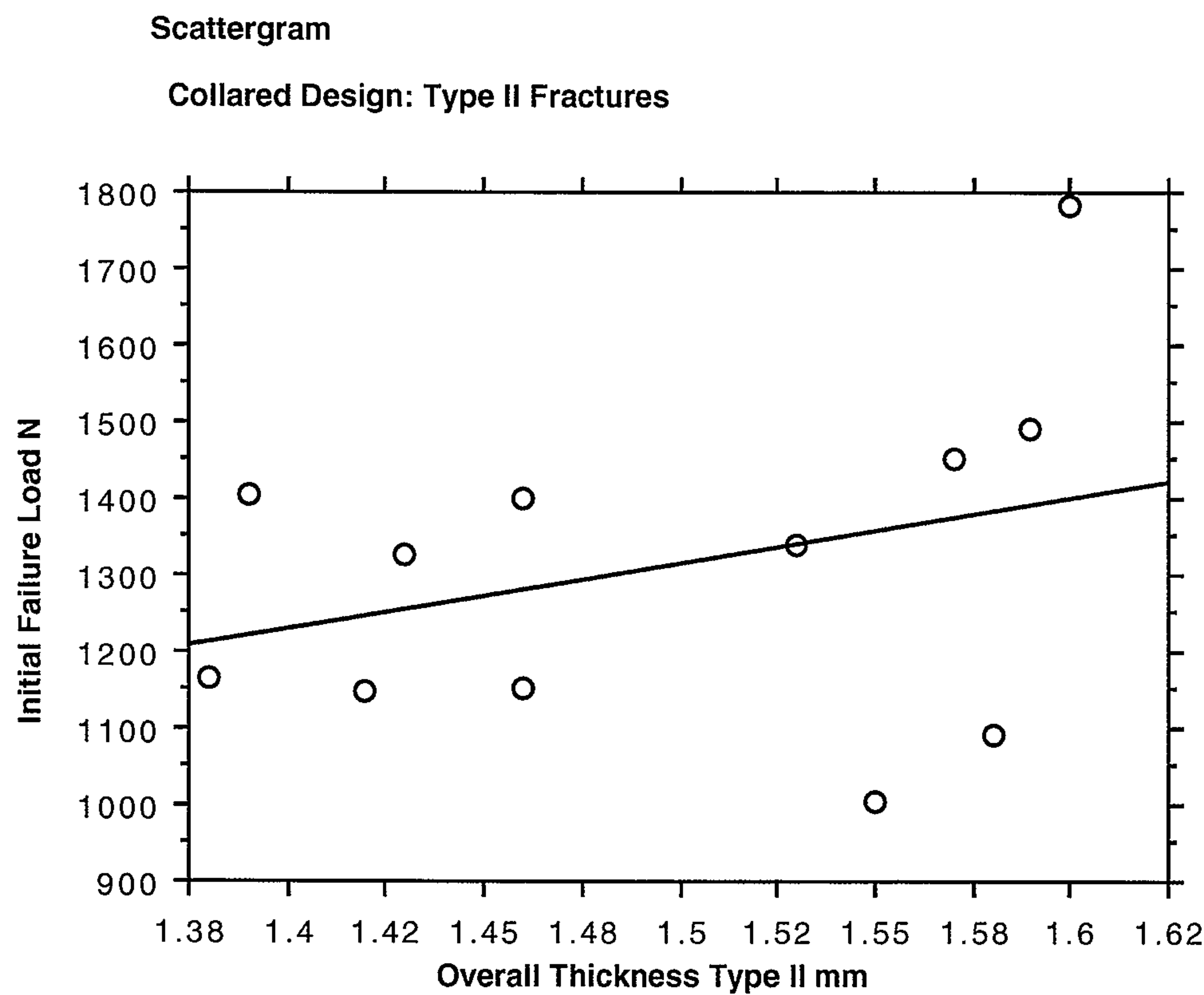


Figure 6.10 Scattergram for the type II results from the collared design group, comparing the initial failure load to the overall thickness dimension.

The result for the overall dimension for type II failures has a slight positive correlation between the thickness and the load. That is, the thicker the crown the higher the load. The scattergrams for overall thickness in both conditions indicate a trend for initial failure load to increase with thickness.

6.3.1.2 Results for the “backed” design crowns.

The analogue results for the crowns designed with In-Ceram palatal surfaces with minimal Vitadur Alpha porcelain are listed in table 6.4 below. The results include measurements of the load for the initial crack and the load when the crown failed completely, i.e. the core ceramic also cracked. The table includes the core and veneer thicknesses for each crown.

The number of crowns with type II fractures is 20 or 83% of the total number for this group. The result is the opposite to the standard design crowns and also different from the collar design crowns where the two fracture types were evenly divided. A summary comparing the loads between the collared and backed designs appears in table 6.5.

The results for this group were also plotted in a series of scattergrams with regression lines to form a view of the trends. The scattergrams for initial failure loads were plotted according to fracture type, core and veneer thickness, and overall thickness.

Table 6.4 Results for the backed design crowns

	Spec ID	Initial Crack load (N)	Load at final failure (N)	Fracture Pattern	Core Thickness (mm)	Veneer Thickness (mm)
Mean	•	1433.292	1450.3		1.186	0.265
Std Dev.	•	307.841	311.2		0.184	0.116
1	B33	1144	1144	II	0.840	0.200
2	B34	1194	1194	II	1.010	0.440
3	B35	884	923	I	1.100	0.110
4	B36	1009	1009	I	1.000	0.150
5	B37	1658	1658	II	1.080	0.340
6	B38	1119	1119	I	1.250	0.290
7	B39	1066	1066	I	1.170	0.200
8	B40	1201	1206	II	1.090	0.100
9	B49	1307	1386	II	1.200	0.210
10	B50	1586	1586	II	0.770	0.490
11	B51	1216	1242	II	1.280	0.370
12	B52	1488	1488	II	1.490	0.310
13	B53	1610	1610	II	1.270	0.200
14	B54	1786	1786	II	1.190	0.300
15	B65	1956	1956	II	1.500	0.300
16	B66	1413	1468	II	1.040	0.410
17	B67	1559	1559	II	1.230	0.310
18	B68	1274	1332	II	1.130	0.230
19	B69	2024	2113	II	1.500	0.100
20	B70	1689	1689	II	1.340	0.290
21	B71	1313	1313	II	1.340	0.260
22	B72	1647	1699	II	1.260	0.320
23	B73	1861	1861	II	1.210	0.140
24	B74	1395	1401	II	1.180	0.390

Table 6.5 **Summary for in vitro failure loads for In-Ceram crowns using two different core designs.**

Modified In-Ceram® Crowns	Mean Load Newtons	Std Dev.
Collared	1185.2	237.8
Backed	1433.3	307.8

Significant difference: $P > 0.0055$

The loads were compared by 1 factor ANOVA with Scheffé test, and a highly significant difference was seen between the Backed group and the Non-collared group from chapter 3 ($P>0.0002$). There was also a significant difference between the Backed and the Collared groups, ($P > 0.0055$). The scattergrams are presented below. The first scattergram demonstrating the core and veneer thicknesses gives clear groupings and trends. The core results have a strong trend for increased thickness to produce increased load for initial failure.

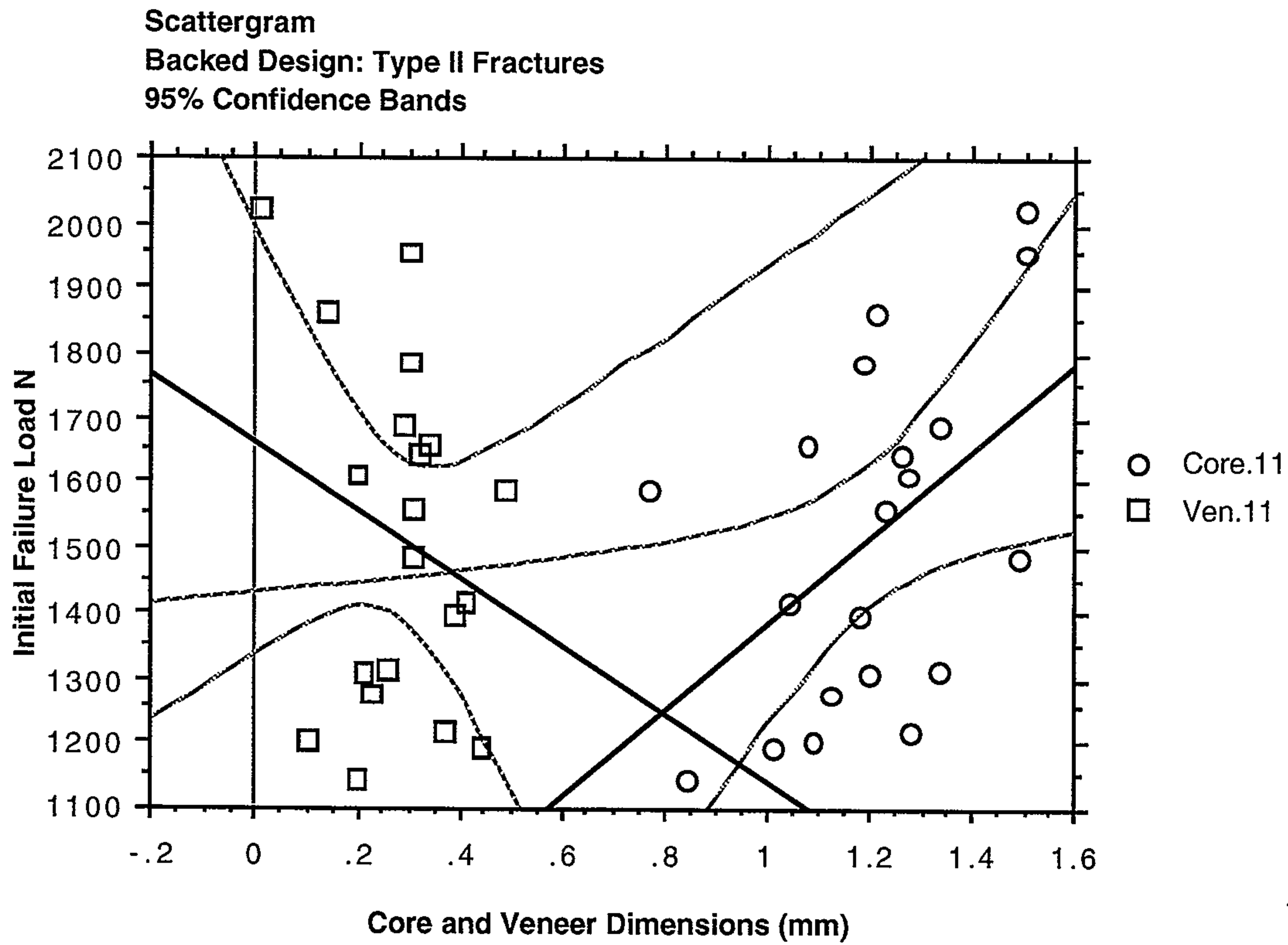


Figure 6.11 Scattergram for the type II results from the backed design group, comparing the initial failure load to both the core and veneer thickness dimensions.

When the group of type II fractures from figure 6.11 are compared with the type I fractures from figure 6.12 it is obvious that the dimensions of the layers for each group are within the same ranges; however the loads are at the low end of the overall range. In terms of core to veneer thickness ratio, the type I fractures had approximate ratios of 1:4 to 1:10. However as the number in this group is only small (4) the only conclusion that might be drawn is that a processing or internal defect may have contributed to the low failure load.

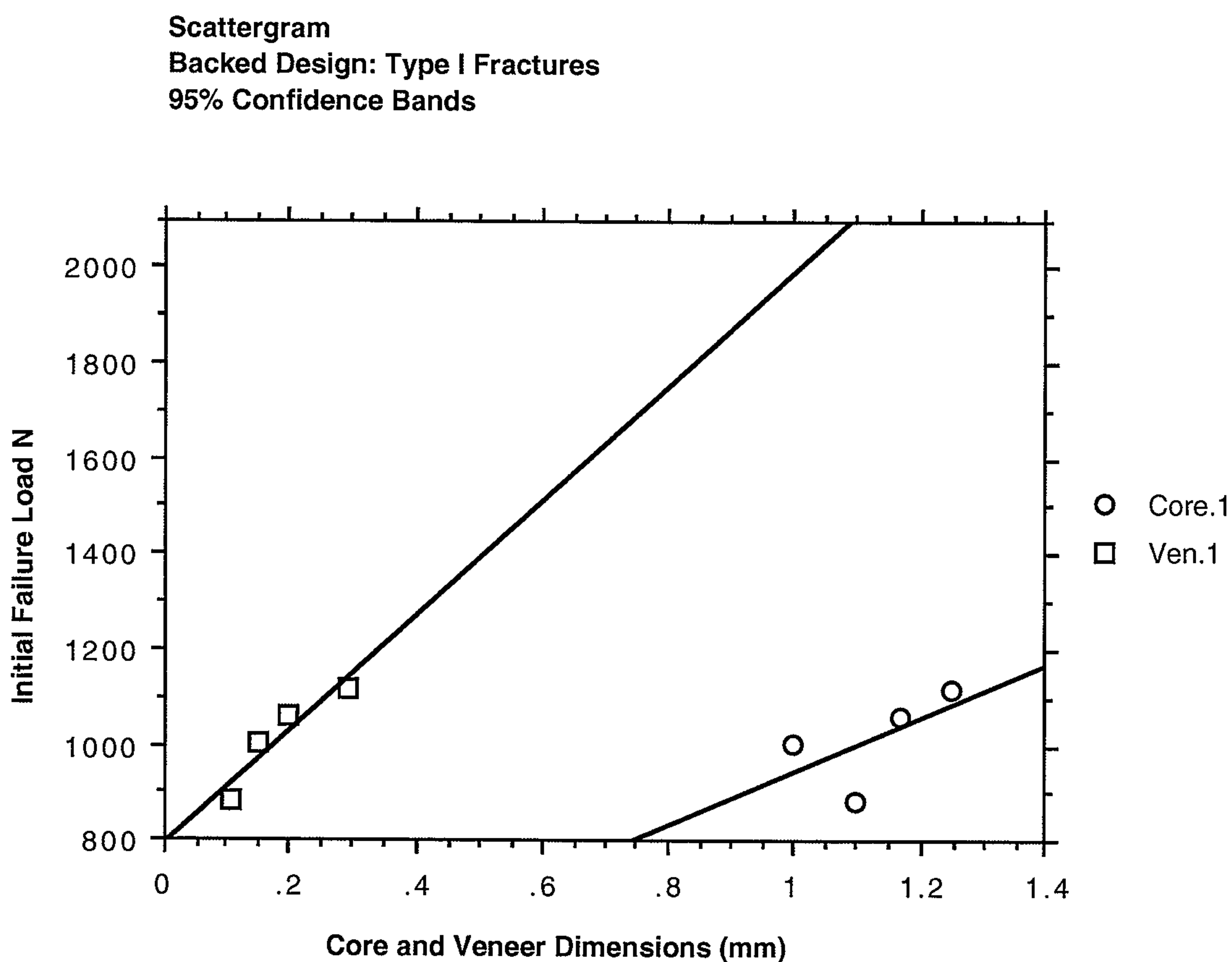


Figure 6.12 Scattergram for the type I results from the backed design group, also comparing the initial failure load with both the core and veneer thickness dimensions.

The following scattergrams in figures 6.13 and 6.14 demonstrate the trend for initial failure load to have a positive correlation to the overall thickness dimension.

Table 6.6 contains a comparison of the correlations between overall thickness and initial failure load and the breakdown of correlations between the layer thicknesses and initial failure load for both fracture types for the backed design. The type 1 fractures have strong correlations for dimension and fracture type, despite their small numbers. This supports the theory that lower forces are required to fracture crowns with thinner overall

dimensions, but not necessarily thinner component layers. The factor, which might be more important for this group is the presence of porosity or residual stress from the manufacturing process for the crown. The data for the type II fractures is mildly supportive of the theory that thinner veneer layers promotes higher loads for initial failure and is more supportive of the theory that thicker cores also promote higher initial failure loads. The difference between the type I and II fractures was that the type I fractures provided evidence that radial cracks in the core layer developed very soon after the cone crack and led to the failure of the crown. The type II fractures were more likely to develop extended cracking and delamination in the veneer layer before the core fractured.

Table 6.6 Correlation values for Type I and II fractures for the “Backed” design crowns.

Initial failure load versus Overall dimension			
	Mean Failure (N)	Correlation Coef.	Fisher's R-Z
Type I (n=4)	1020	0.772	0.3049
Type II (n=20)	1516	0.386	0.0934
Initial failure load versus Core thickness			
Type I (n=4)	1020	0.599	0.4896
Type II (n=20)	1516	0.492	0.0265
Initial failure load versus Veneer thickness			
Type I (n=4)	1020	0.923	0.1082
Type II (n=20)	1516	- 0.232	0.3307

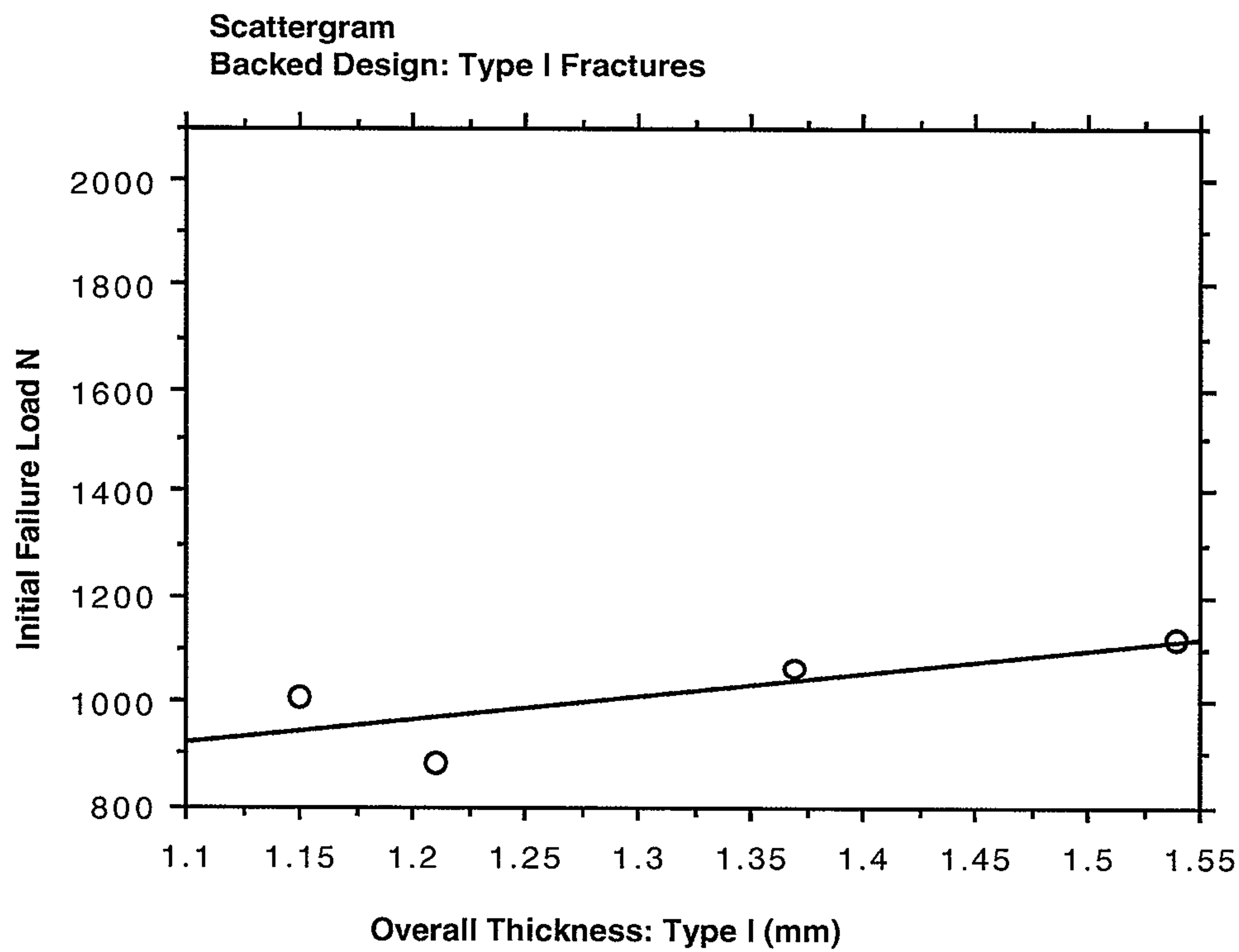


Figure 6.13 Scattergram for the type I results from the backed design group, comparing the initial failure load with the overall thickness.

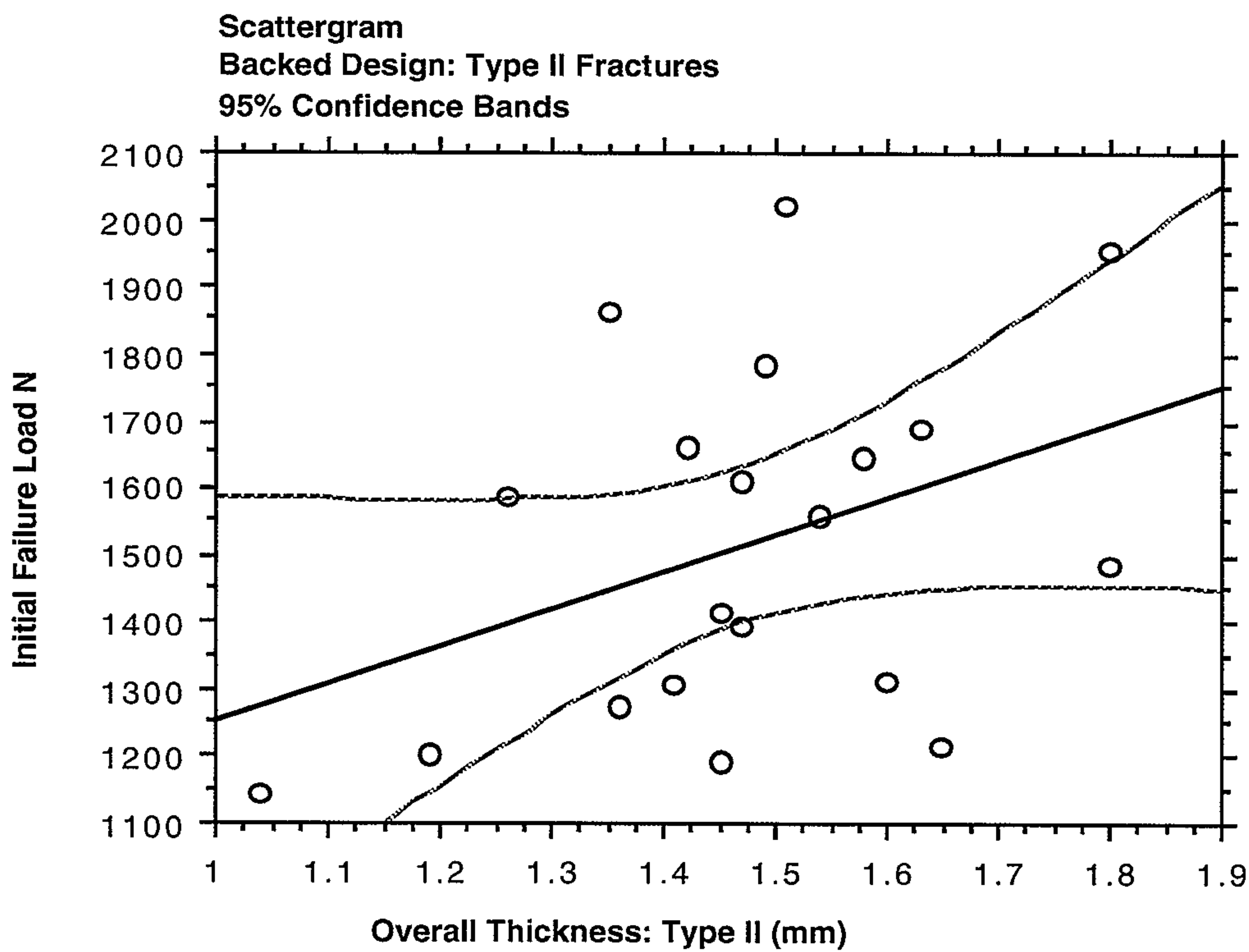


Figure 6.14 Scattergram for the type II results from the backed design group, comparing the initial failure load with the overall thickness.

6.3.2 Comparison of fracture patterns, loads and crown designs.

An overall comparison of the results with the fracture pattern classification is given in table 6.7 below. The significance is not in the mean of the loads, but in the fracture pattern. The collared group with core veneer dimensions at the contact point that are not dissimilar to the non-collared group display an almost even number of type I and type II fracture patterns.

Table 6.7 Comparison of initial crack loads and fracture patterns; load values are in Newtons.

Non-Collared		Collared		Backed	
Load	Fracture Pattern	Load	Fracture Pattern	Load	Fracture Pattern
795	I	1020	I	1144	II
855	I	1003	I	1194	II
551	I	1781	II	884	I
1275	I	1337	II	1009	I
1337	II	1266	I	1658	II
1424	I	1085	I	1119	I
1191	II	860	I	1066	I
1466	I	1330	I	1201	II
1198	I	1109	I	1307	II
1078	I	1105	I	1586	II
998	I	1404	I	1216	II
1201	I	1492	II	1488	II
1145	I	1400	II	1610	II
1465	I	1198	I	1786	II
1378	II	1005	II	1956	II
1322	I	1151	II	1413	II
629	I	1090	II	1559	II
1187	II	731	I	1274	II
885	I	1452	II	2024	II
844	I	928	I	1689	II
1055	I	841	I	1313	II
802	I	1406	II	1647	II
1149	I	1148	II	1861	II
1061	I	1324	II	1395	II
1192	I	1164	II	*	*

When all the crowns were grouped according to the fracture pattern the results were also significant using ANOVA with 1 factor Scheffé. The results appear in table 6.8. There appears to be a significant difference in fracture pattern despite there being only 0.177 millimetres difference in core thickness. A further summary comparing the number of type I and type II patterns is found in table 6.9.

6.3.3 Comparison of layer thicknesses.

The loads at initial failure and the thicknesses of the layers were compared for all crowns with the distinction between the groups being made purely on the empirical grounds of fracture type. An additional comparison was made by comparing the crowns from the two modified designs.

Table 6.8 **Summary of mean initial crack loads vs average core thickness and average veneer thickness for different fracture patterns; load values are in Newtons.**

	Load (N)	SD	Core Thickness (mm)	SD	Veneer Thickness (mm)	SD
Type I (n=38)	1061.8	224.6	0.693	0.22	0.572	0.2
Type II (n=36)	1421.2	254.9	1.043	0.254	0.407	0.212
p value	< 0.0001 (s)		< 0.0001 (s)		0.0023	

Table 6.9 **Summary comparing the fracture pattern frequency for each group.**

	No Collar	Collared	Backed
Type I Pattern	21	13	4
Type II Pattern	4	12	20

6.3.4 Weibull Plots and Moduli Results.

Weibull statistics were also employed for evaluation of the probability of fracture of the two new design groups. These were plotted and the results would indicate reasonable consistency for each Weibull modulus. In terms of the overall result these plots and moduli help to confirm the reinforced design as a better option to resist fracture initiation

from occlusal contact. The plots appear in figures 6.15 to 6.20, with emphasis being placed on the slope and the intercept at $\ln\ln(1/1-P_f) = 0$.

The results do not indicate a significant difference in reliability when compared by design but there does appear to be a significant difference when compared by fracture type for all crowns. Similarly the Weibull plots and moduli were compared for the two modified designs only, separating them on the basis of fracture type.

In figure 6.15 the intercept occurs on the x – axis (ln-load) occurs at a value of approximately 14.05 which is an approximate load of 1266 N. The value for this intercept in figure 6.16 is approximately 14.27, which translates back to an approximate load of 1570 N. This compares with an intercept of approximately 13.9 with a load of 1078 N for the standard crowns in figure 3.25. The Weibull moduli in figures 6.15 and 6.16 are not significantly different, but the loads are, indicating similar reliability but with the reinforced palatal surface able to sustain higher loads.

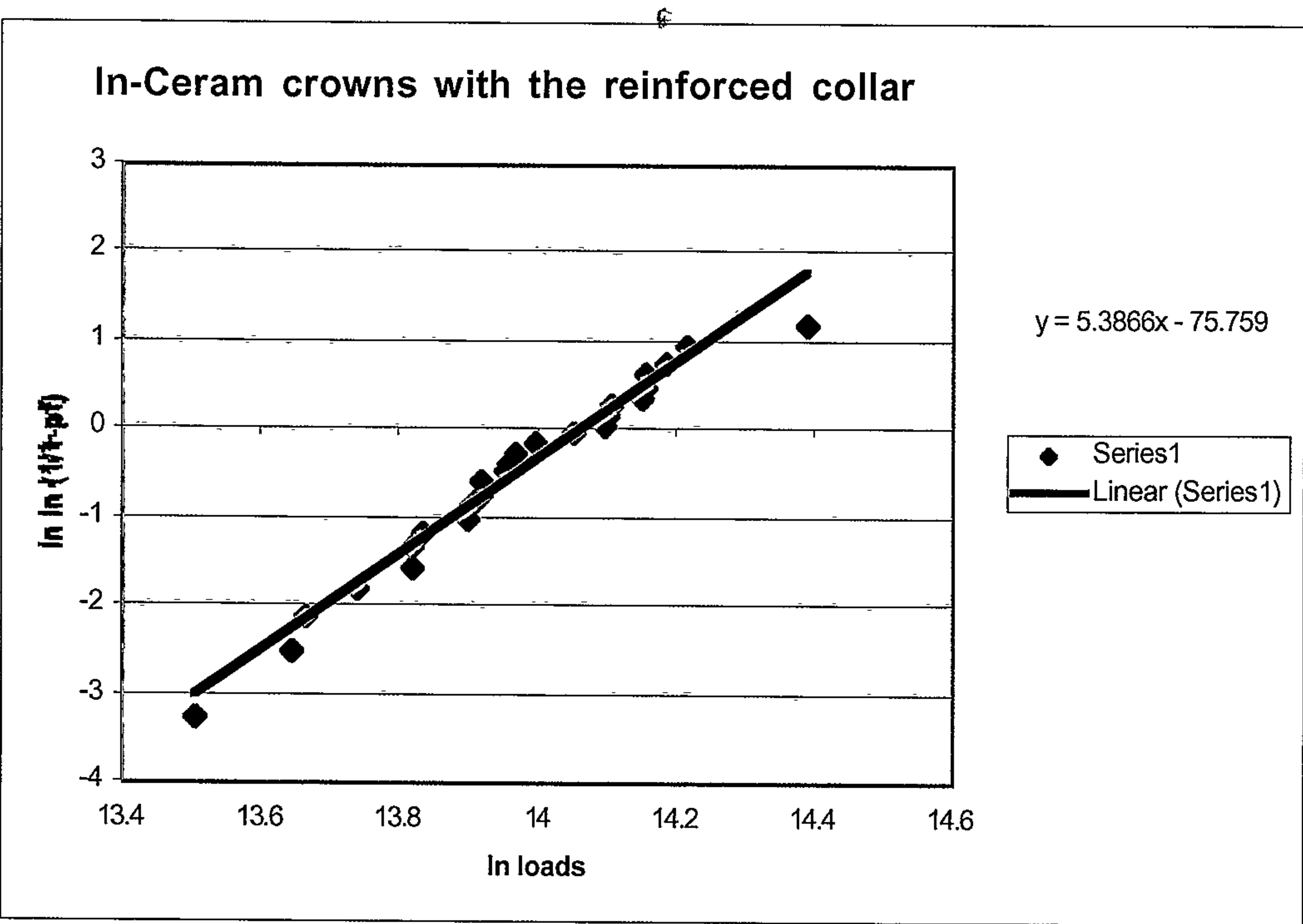


Figure 6.15 Weibull Plot for the crowns with the extra core thickness on the palatal surface in the gingival collar area only.

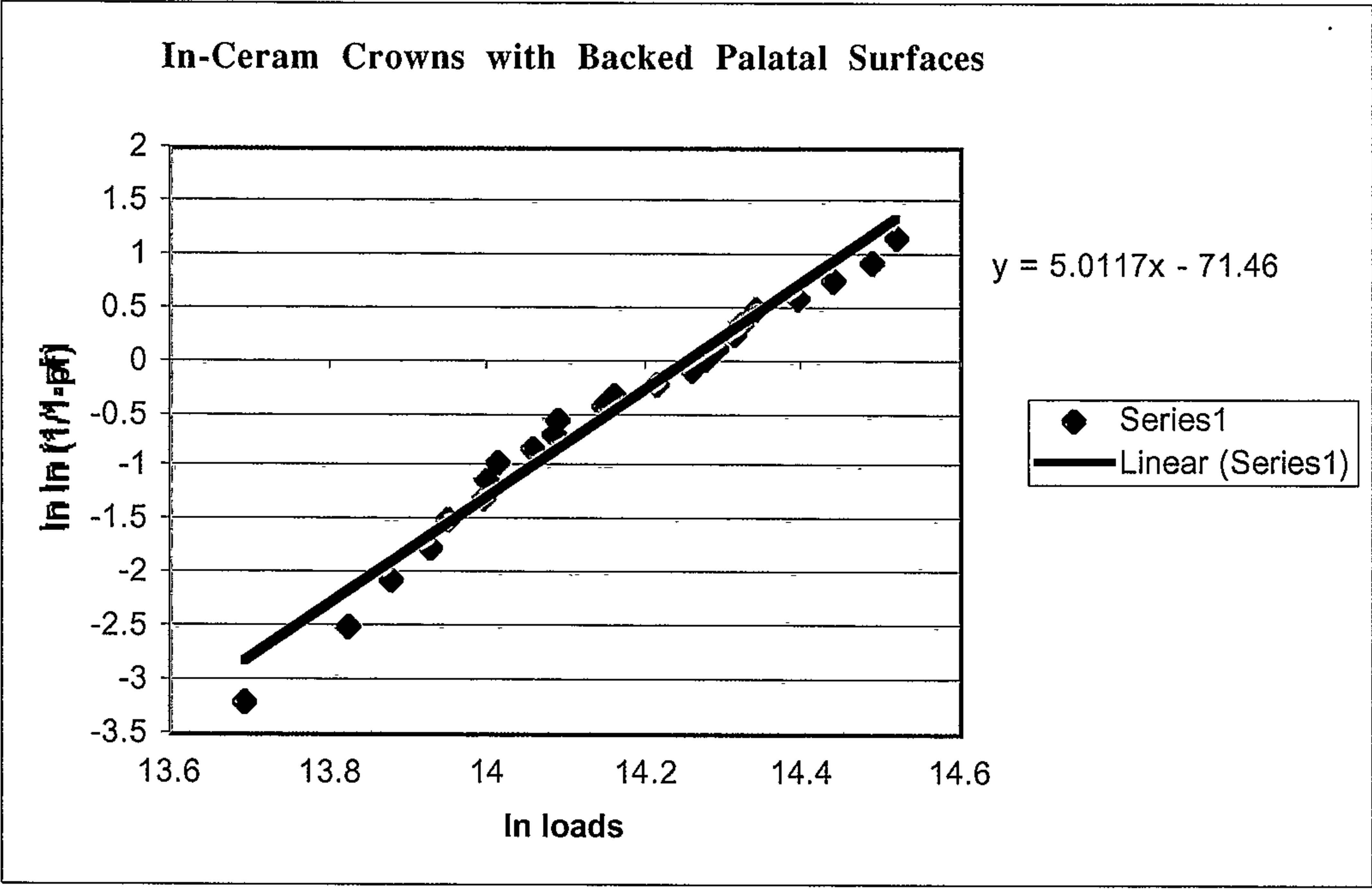


Figure 6.16 Weibull Plot for the crowns with the extra core thickness on the palatal surface.

The plots in figures 6.17 and 6.18 represent the Weibull statistics for the two different fracture types for all the crowns tested, that is the standard crowns in chapter three and the two groups from this chapter. These fracture types were based on type I being a cone crack as the initial failure followed by a radial crack and type II which has a cone crack start with crushing and delamination and radial cracks for final failure. The Weibull moduli in this case are different at 5 and 6.3 respectively. Significantly, the x – axis intercepts are 13.91 and 14.4 respectively which translate to a load of 1100 N for all type I fractures and a load of 1786 for type II fractures. The significance is that the crowns which have a type II fracture are both more reliable and their fractures are likely to occur at significantly higher loads. The level of the load is significantly higher than that reported in table 3.4.

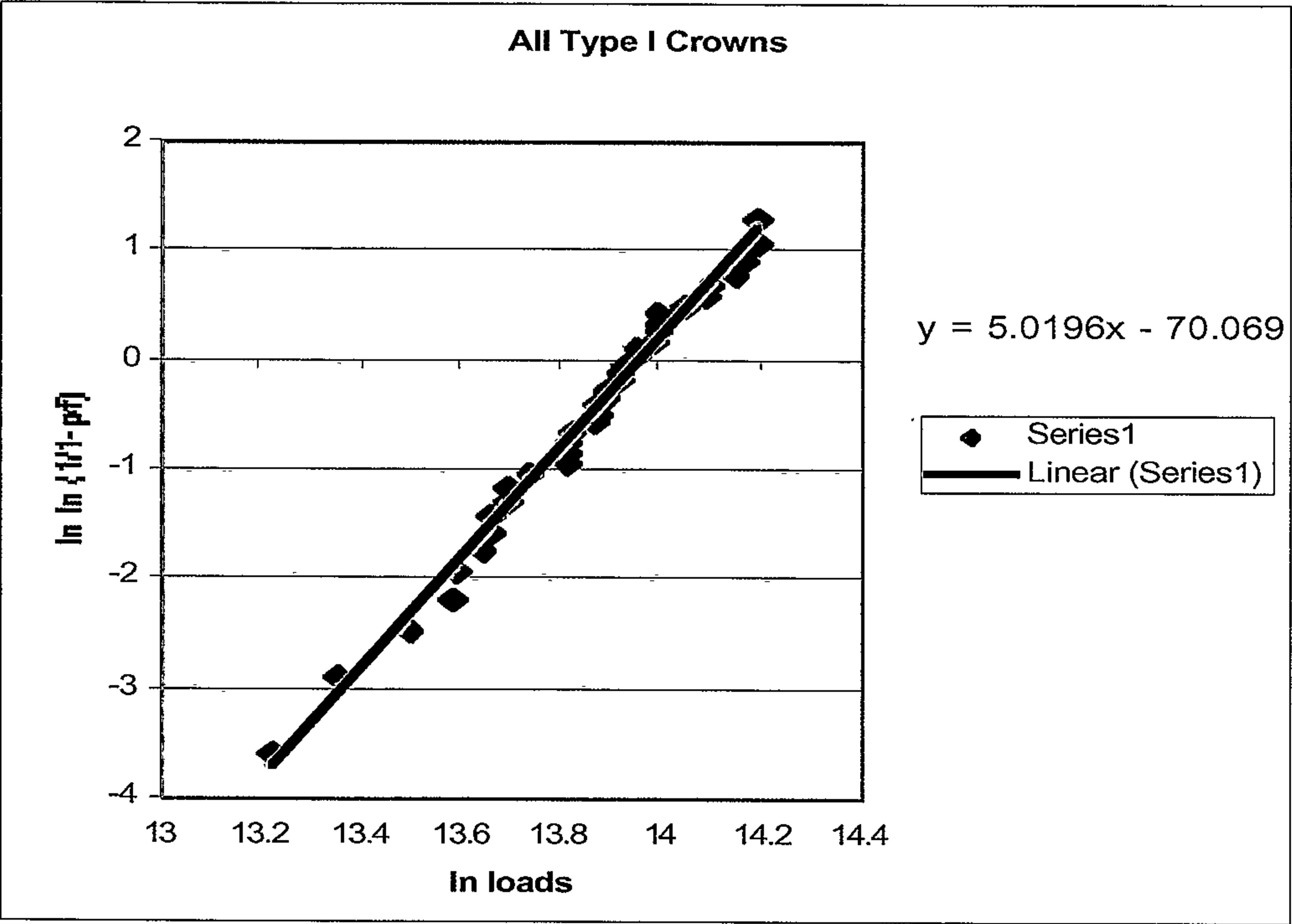


Figure 6.17 Weibull Plot for the crowns designated as Type I based on the observed fracture pattern.

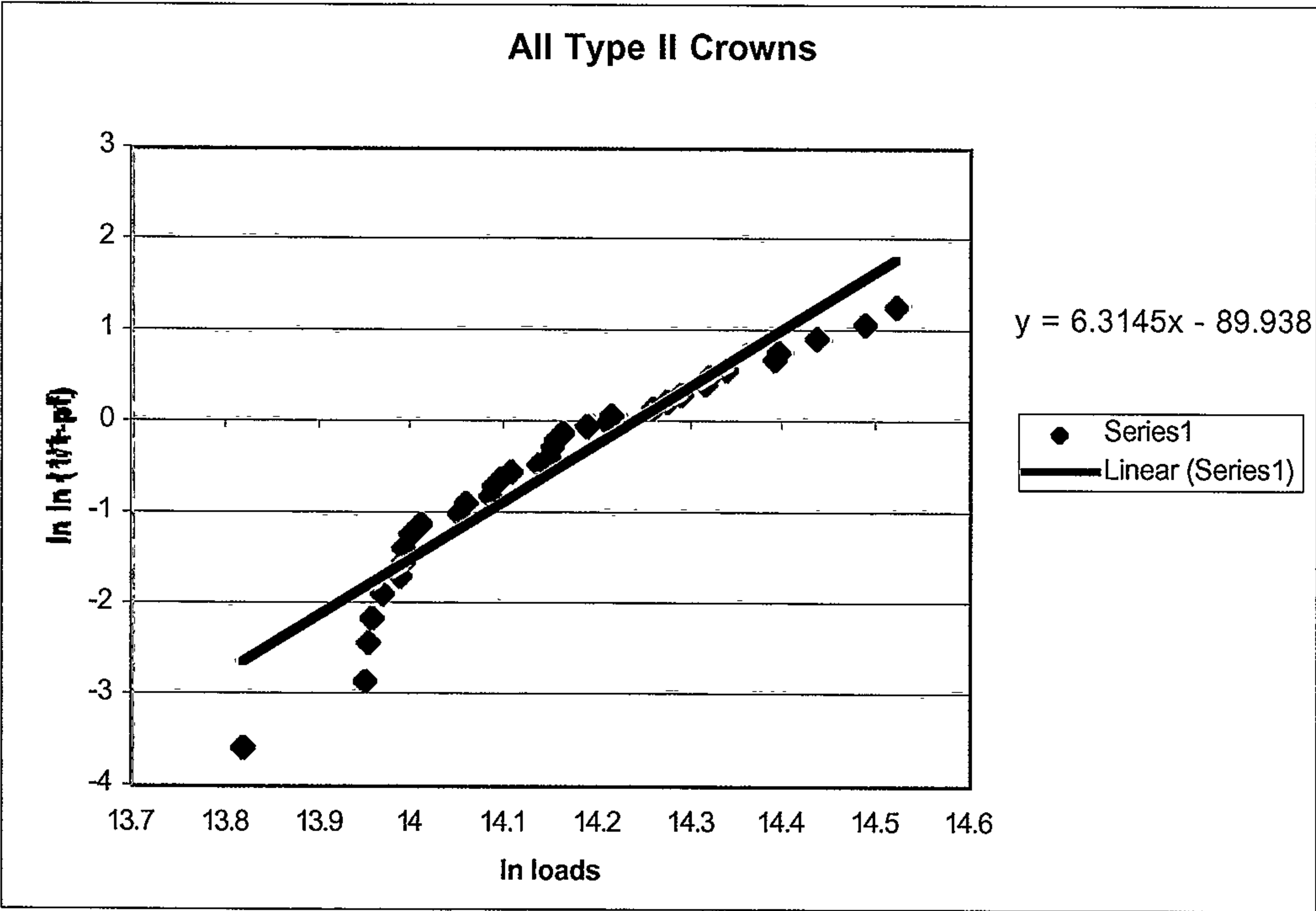


Figure 6.18 Weibull Plot for the crowns designated as Type II based on the observed fracture pattern.

Similarly the plots for type I and II fractures from the two modified designs displayed in

figures 6.19 and 6.20 exhibit a trend for the type II fractures to have similar reliability values (6.2 and 6.1 respectively) but the type II fractures occur at a higher load, 1560 N versus 1120 N.

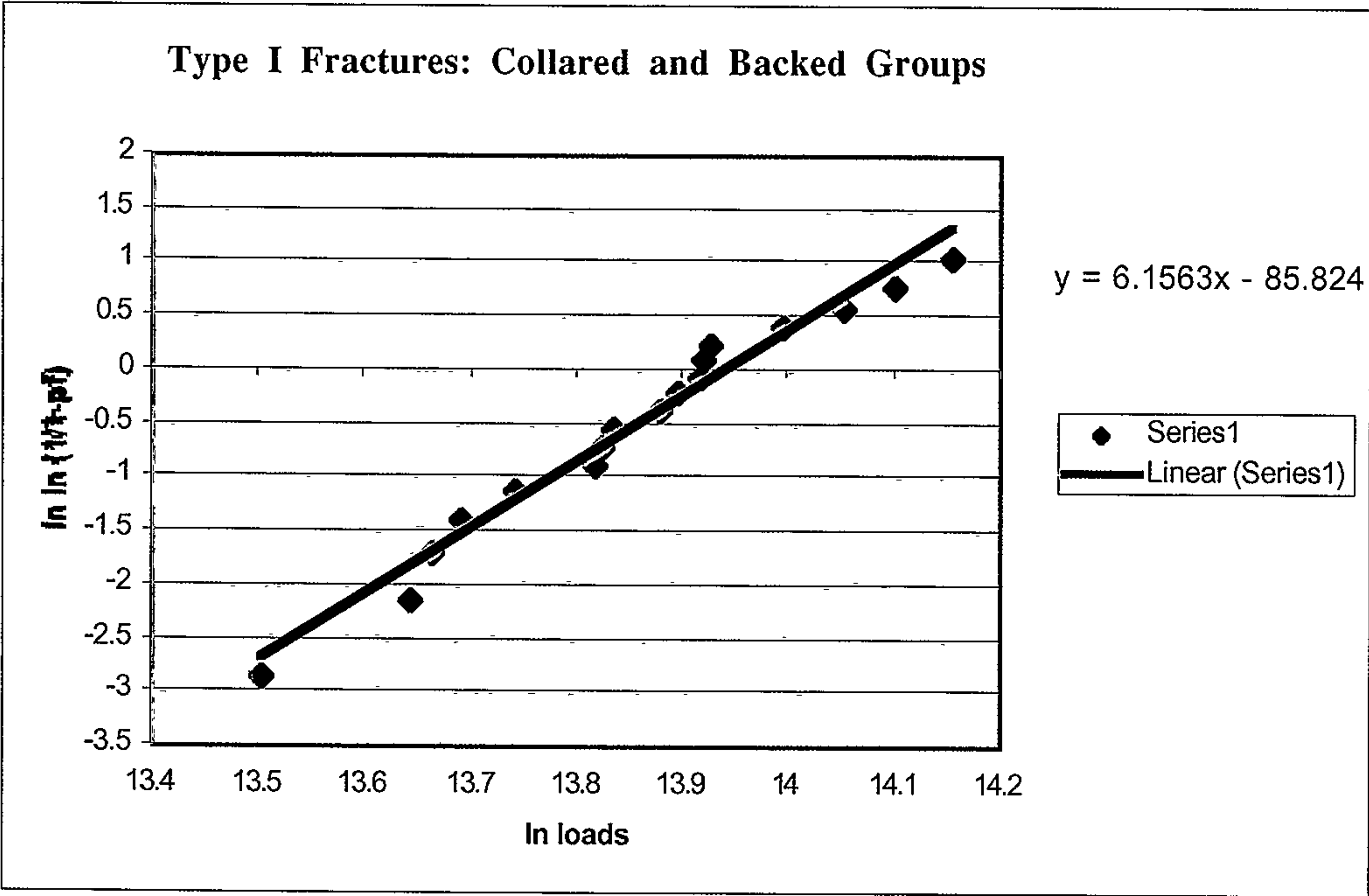


Figure 6.19 Weibull Plot for the crowns from the two new designs and designated as **Type I** fractures based on the observed fracture pattern.

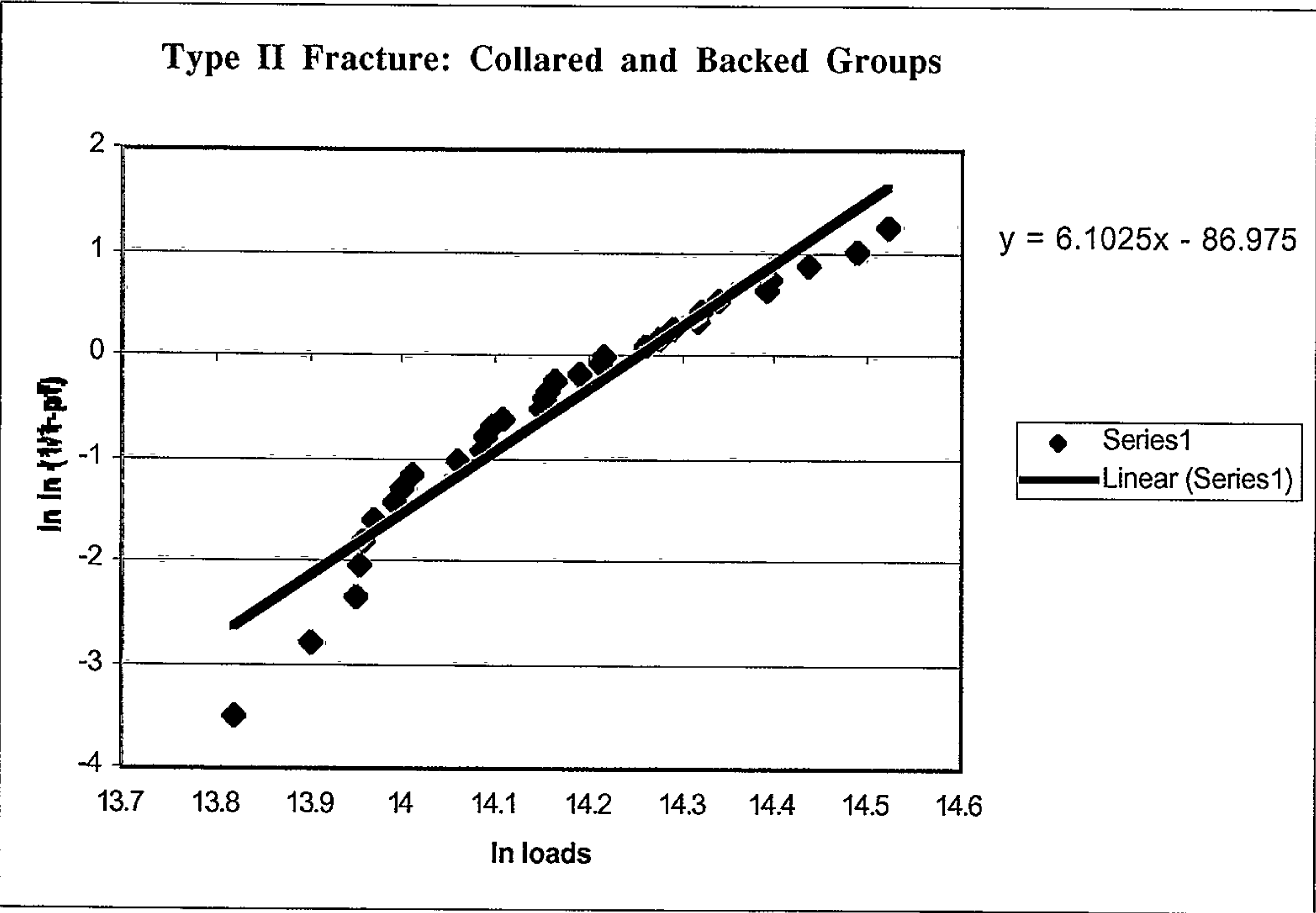


Figure 6.20 Weibull Plot for the crowns from the two new designs and designated as **Type II** fractures based on the observed fracture pattern.

Table 6.10 Summary of Weibull Moduli for different combinations of crown results.

Group	Weibull Modulus	Intercept $y = 0$ & Load (N)
Collared Group (Crowns with Reinforced Palatal Collars)	5.4	14.1, 1329
Backed Group (Crowns with Reinforced Palatal Surfaces)	5.0	14.3, 1623
Type I Fracture: All Crowns	5.0	13.96, 1155
Type II Fracture: All Crowns	6.3	14.24, 1529
Type I Fracture: New Designs	6.2	13.94, 1133
Type II Fracture: New Designs	6.1	14.25, 1544

6.4 Discussion.

The thickness of the core and the proximity of the core to the surface of the crown appear to have significantly influenced the crack initiation load and the directions of the cracks. Comparison of the layer thicknesses for the two types of fracture patterns showed a significant difference in the load required for fracture, $p > 0.0001$, see table 6.8. The crack paths tend to spread more along the boundary between the two layers for the backed group which indicates that the tensile bond strength between them, and the fracture toughness of the core material have a significant role in crack deflection and/or propagation. Indeed a number of physical parameters come into play to determine the crack direction. These include the difference in elastic modulus between the two, the fracture toughness of the two materials and the fracture toughness of the interface.

The slopes of the Weibull plots, or the Weibull moduli, for the two specific design variations do not have a significant difference, however, when all the crowns are separated according to their fracture pattern, the Weibull plots are significantly different, indicating that the crowns from type II are both stronger and more reliable. There is a slight difference between the Weibull moduli for the standard design and both modified designs. This provides sufficient information to recommend the modified designs on the basis that the type I fractures came from crowns which generally had core to thickness ratios in the order of 1:1, and the type II fractures generally had core to thickness ratios that were generally greater than 2:1. The statistical difference between initial failure loads between the collared and backed designs provides further evidence that the latter design should be

preferred wherever possible. The statistical data is confirmation of the results from chapter five, where it is evident that the thickness of the core layer is very significant in preventing failure.

The other parameter from the Weibull plots which demonstrates a significant difference in the failure probability between the two fracture types is the relationship between the load value of type II fractures occurs, where the type I fracture intercept at $\ln \ln(1/1-P_f) = 0$. This is seen in figure 6.21. At this particular value for type I, the $\ln \ln(1/1-P_f)$ value for type II is approximately -2 . The $\ln \ln$ value means that the probability of failure by a type II fracture is 5 to 10 times lower for the same load. The result is that crowns with type II fractures are much more likely to survive. To put this in context with the physical dimensions of the layers, the type II fractures were predominantly from the Collared and Backed designs, principally the Backed designs and the mean core to thickness dimensions for the backed group were approximately 1.2 to 0.27 mm respectively.

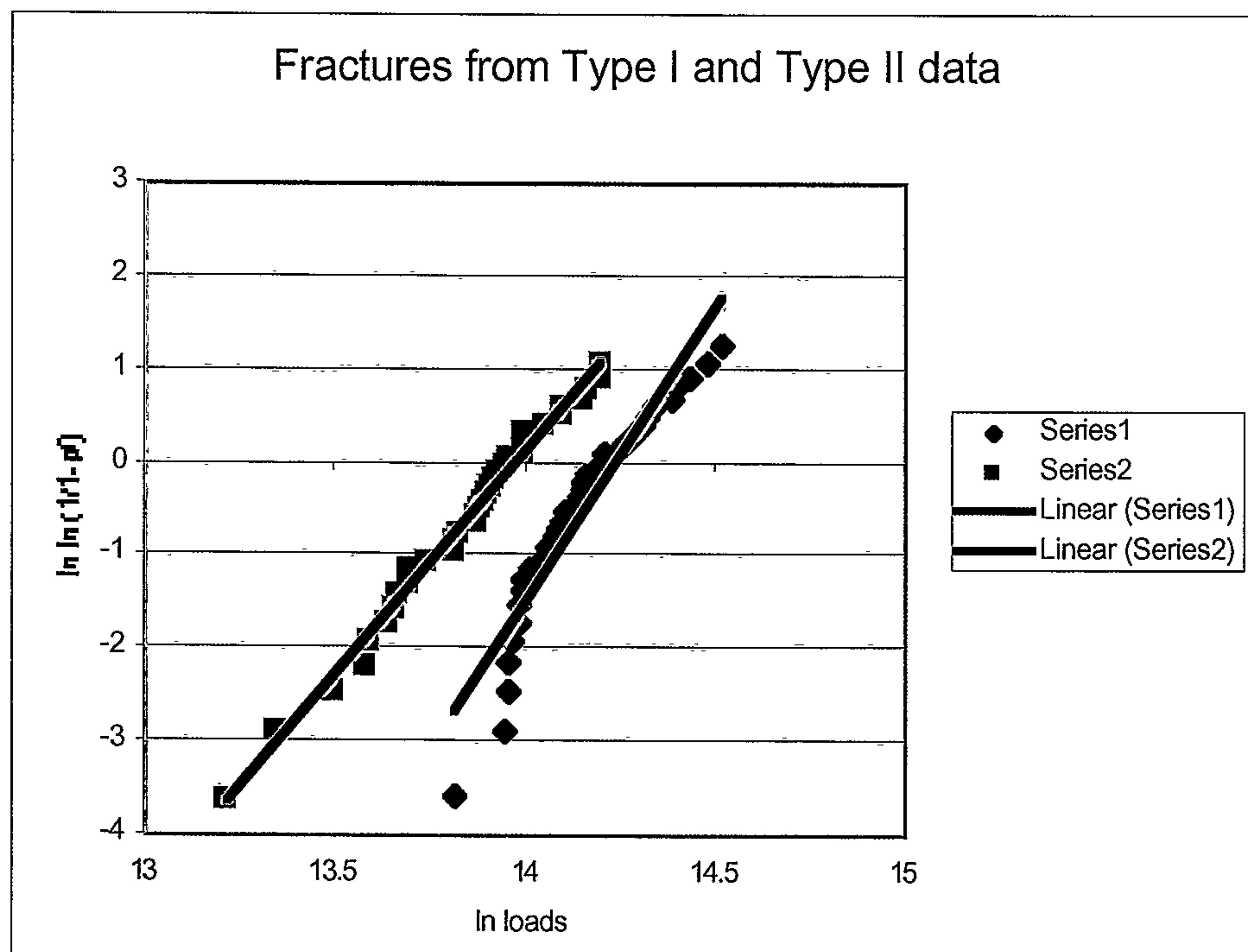


Figure 6.21 Comparison of Type I (Series 1) and Type II fractures (Series 2).

The data from the Weibull statistics indicates that those crowns which exhibited the Type II fractures were both stronger and slightly more reliable, (Weibull modulus is higher).

The analytical results from chapter five indicate that a core to veneer ratio of 2:1 has a higher load for fracture initiation. When this is applied to the type II crowns with the same ratio or higher, which generally placed them in one of the two new designs, the Weibull plot and modulus are as follows, in figure 6.22.

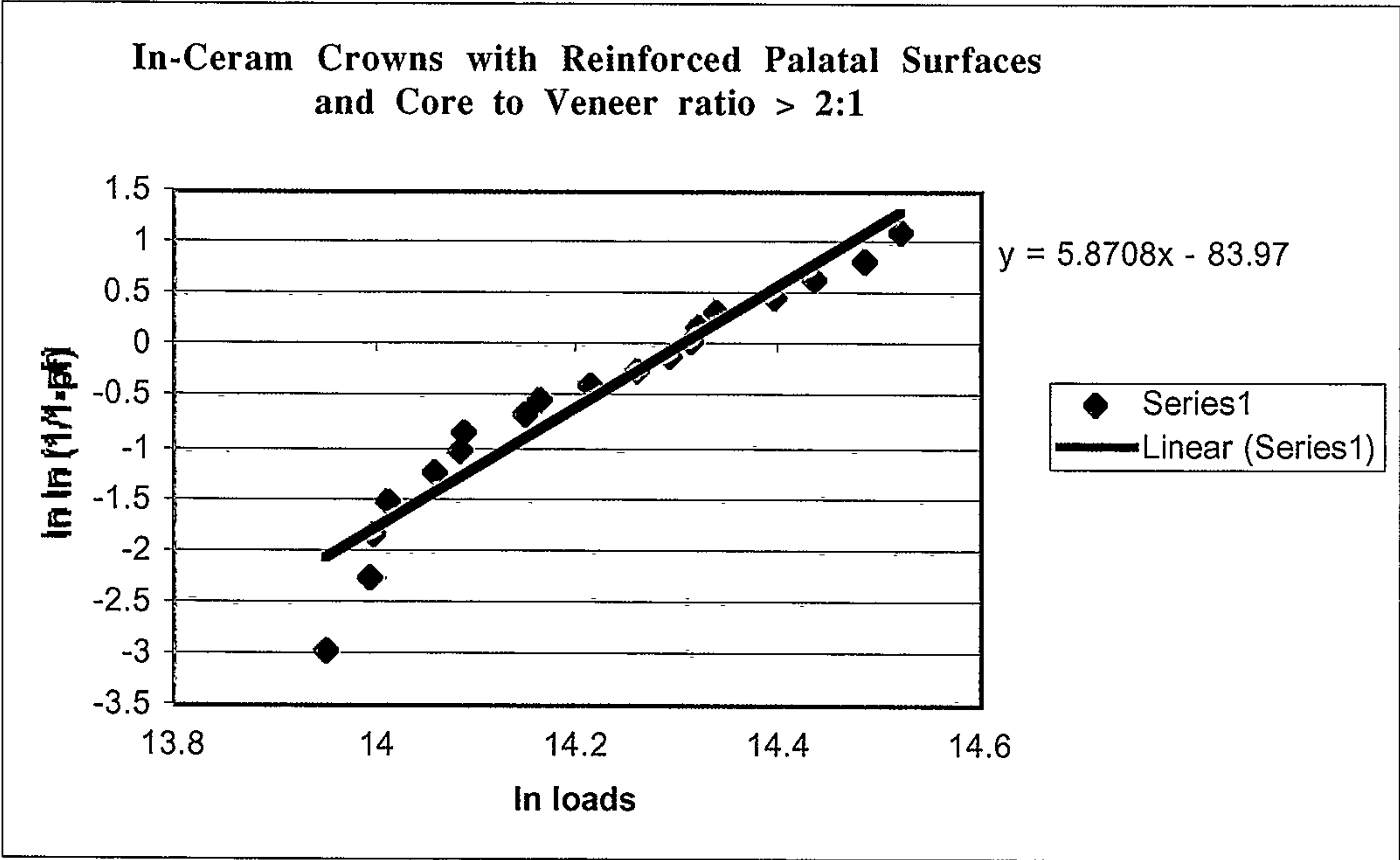


Figure 6.22 Type II crown fractures where the core to veneer thickness ratio is greater than 2:1. These crowns were therefore mainly from the new design groups.

In terms of failure probability (from the slope of the Weibull plot) the 2 : 1 thickness ratio of the core to the veneer, does not show any significant difference, perhaps slightly poorer, however the load level for failure is approximately 1660 N. The critical tensile stresses involved at the contact point and the underside of the core layer therefore need to be critically evaluated. The conditions to create the critical stresses in these tests were to simulate a worst case scenario, that is to provide a margin of reliability that would be acceptable clinically. For most situations, particularly for anterior crowns, the loads involved are lower than those created in these tests. The Young's modulus of the antagonist is often enamel (approx. 70 GPa) and the contact stresses encountered are much lower than those for steel. The failure probability predicted on the basis of contact loads and Weibull moduli, from these experiments, are therefore conservative.

However, as stated earlier, a patient with an occlusion that in part has a steel denture, or stiff ceramic, e.g. alumina, opposing a porcelain veneered crown such as Vitadur Alpha on In-Ceram could be at risk of fracturing the crown in the areas of porcelain not directly supported by the core or where the porcelain is also thick relative to the direction of the applied force. An example would be where the tendency for thick veneer coverage at the proximal margin of an anterior or posterior crown could easily be subject to critical stresses sufficient to fracture that part of the crown. Therefore, referring back to Auerbach's law, ($P_c \sim AR$), to initiate cracking under anatomical forces (typically 200 – 400 N) would require an antagonist with a radius of 0.5 to 1 mm.

6.5 Conclusions.

The conclusions drawn are that:

1. A spherical insult not dissimilar to an opposing tooth contact can cause an initial crack capable of destroying this type of crown.
2. In all cases failure started from the crack initiation site (i.e. the indenter) and not from the internal fit surface.
3. The initial fracture on the surface was not necessarily the fracture that caused the ultimate fracture of the crown, particularly for those crowns where the porcelain crushed and delaminated.
4. A design with a greater thickness of core material at the contact point is significantly stronger than the conventional design and has a much lower risk of failure than crowns from the standard design at the same loads.
5. A 3 dimensional finite element simulation might provide a clearer indication of crown design given that the scatter plots did show wide variation in some cases.

CHAPTER 7

Summary

The commercial introduction of glass infiltrated slip cast alumina ceramic technology as a core dental ceramic for crowns and bridges began in 1990. The system known as In-Ceram® provided a metal free ceramic core with a flexural strength that was reported to be between 400 and 600 MPa. This was up to three times stronger than any previous dental ceramic. With the widespread introduction came early failures as dental technicians and dentists learnt to adapt to this new technology. The fractures fell into the first part of the “Bath-tub” curve described by Lawn (1993). The primary aim of this study was to investigate in vitro fractures for this type of crown that occurred from high, localized occlusal loading. A secondary aim was to propose suitable guidelines for the construction of crowns that are more crack resistant when loaded by a spherical object such as an opposing cusp.

A review of the literature identified Young’s modulus (E) as an important aspect for the behaviour of a brittle solid when it is exposed to load. Young’s modulus is involved in the total energy of the solid, its free surface energy, its toughness, parameters involved in contact areas, stresses from indenters on those contact areas. The review also pointed out the importance of the Young’s modulus mismatch at the interface between two materials with different moduli when the adhesion between them was subject to crack propagation. This mismatch was to become more obvious when Finite Element Analysis was applied to determine the stress associated with the test results. A second physical property that has importance in bilaminar materials is Poisson’s ratio. Less important than Young’s modulus, it still provides some indication of the crack propagation at an interface, highlighted by the description of Dundurs parameters (Mencík 1996). The use of Weibull statistics provided information concerning reliability for different core to veneer thickness ratios in the experimental models and crown designs.

The initial experimental component of this thesis was to establish a clinically relevant crown model suitable for investigation. The porcelain jacket crown restoration for an

upper incisor was chosen because it provided the best opportunity to vary the construction parameters of the crown without sacrificing the aesthetics. It was also considered that a posterior crown could more readily display core material at the surface should the new design require it. The display of core material on the surface of the tooth was not deemed aesthetic, and aesthetics are one of the main criteria for the use of these crowns. The results from this initial in vitro study established the thickness ranges for the standard design of these crowns, and the loads that could be expected. In addition two types of fracture patterns were identified that occur when the bilaminar system is loaded via a hard steel ball indenter. It was also noted that the adhesion and support of the core affected the results. The loading position in the middle of the palatal surface was chosen for its relative simplicity when comparing the bilaminar structure in this area with other known methods for measuring physical and mechanical properties of the materials.

The data from chapter 3 was then compared with two basic bilaminar and monolithic disc designs to establish the relevance of the dimensions of the ISO standard test specimen design for flexural strength. The results of this chapter confirmed that the loads were in the same range for the bilaminate discs, and that the flexural strengths for the two component parts were in agreement with other known results. The use of Finite Element Analysis (FEA) was employed to provide an additional method for evaluating the model to establish areas and magnitude of principal stresses. It was found that the ISO flexural strength test was not ideal for testing bilaminates because it did not account for the large mismatch in Young's modulus between the two component materials. The FEA revealed that the magnitude of the tensile stress on the bottom surface of the In-Ceram was much greater than the analytical solution when it was the bottom layer in a bilaminate. Also the flexural test did not provide accurate information about the effect of support beneath the discs on the stress developed during loading. The FEA did confirm the difference between a flat punch and a ball indenter for stress intensities around the contact area with the ball indenter producing higher stresses for a given load. Data from this chapter provided information about the effects of thickness variations for the two component materials on the overall load to failure. The stresses at the surface were calculated using a novel analytical program called "Elastica".

The following chapter (chapter 5) was designed to test the effect of supporting the ceramic system with different ceramic core layer thicknesses. This was the second step in gaining information about the design criteria for a more crack resistant crown. The physical tests were made using a 5 mm diameter steel ball on discs that were supported on a flat steel base. The FEA results indicated again that the tensile stresses on the bottom surface of the In-Ceram were higher when it was used in combination with the Vitadur Alpha veneer, but that the level of stress was much lower than that experienced in the unsupported state. An

FEA model using the properties of dentine as the support base also confirmed a significant influence from this medium. As the Young's Modulus of the support and the relative thickness of the In-Ceram increased, the tensile stress on the bottom surface decreased. As the support increased and the veneer thickness decreased, the stresses on the top surface of the Vitadur Alpha increased, and the nature of the damage changed from a simple cone crack followed by radial cracking, to a complex cone crack and crushing of the veneer porcelain. The high pressures in the thinner veneer layer crushed the contact area. Then radial cracks followed. The higher pressures on the thinner veneer layers caused those samples to break explosively.

The above information was then integrated and applied to the design of crowns, where layer thicknesses were altered under normal dental laboratory conditions. The less controlled dental laboratory environment was used to test whether the expectations for design change were achievable. The layering process for building these crowns provided a range of veneer thicknesses, but by adhering to the basic guidelines, the modified crowns statistically performed better under the loading conditions used with Weibull moduli of 5 to 6 compared with 4 for the standard crowns. The mean load for failure of the backed group was significantly higher than either of the other groups. The results from the modified crown tests confirmed the data in chapter five, where it was shown that increasing the In-Ceram thickness and decreasing the Vitadur Alpha thickness at the point of contact could provide a more reliable crown during function.

The implications from this in vitro study are:

1. There is a significant influence in the type of support beneath these crowns at the point of occlusal loading.
2. The surface finish of the tooth core preparation may have a significant influence on the fracture resistance. This is with respect to the adhesion of the luting agent to the tooth surface irrespective of whether the actual adhesion is to dentine or an artificial core such as gold, ceramic or resin.
3. The overall design of the core layer with particular respect to the area beneath the contact area has been shown to influence the initiation of fractures and in some respects the propagation of those fractures, although it is recognized that once the porcelain has fractured the crown is, for all intents and purpose, a failure.

A summary of the three core designs is given in figures 7.1 and 7.2.

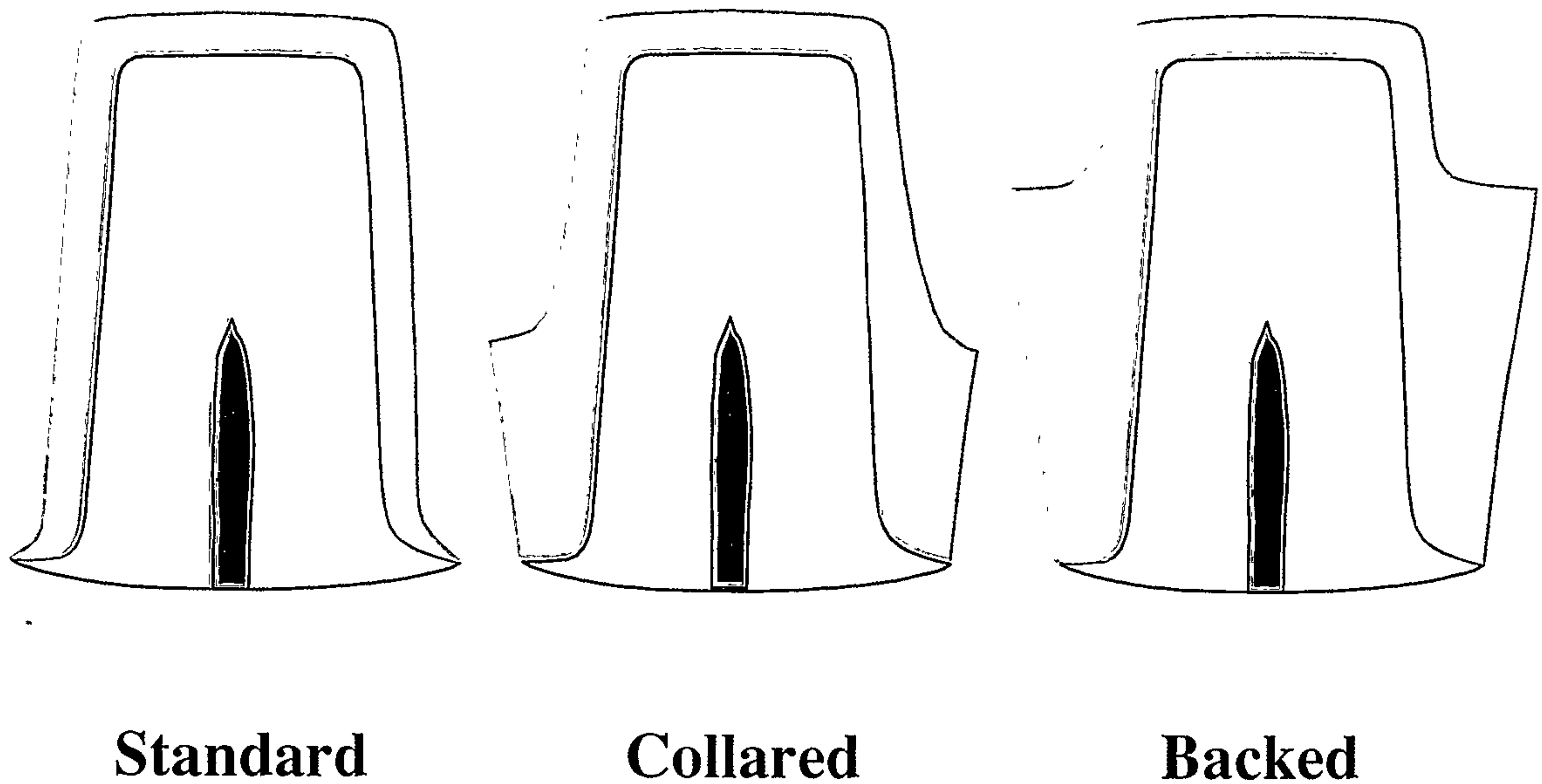


Figure 7.1 Labial view of the three core designs for an anterior In-Ceram® crown.

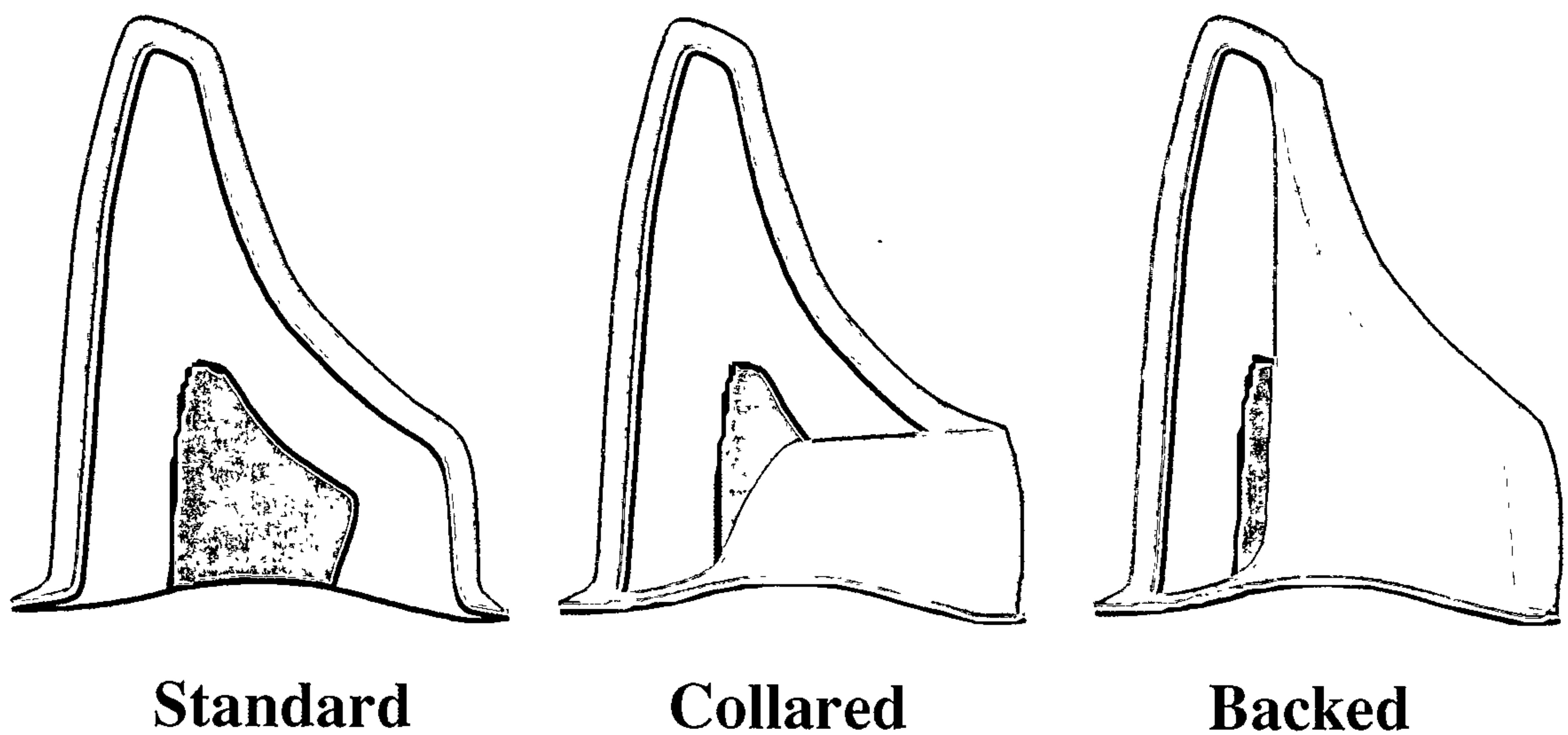


Figure 7.2 Proximal view of the three core designs for an anterior In-Ceram® crown.

The directions for future research include the following:

1. The effect of other types of core layer with lower Young's moduli, such as alumina/zirconia mixtures, on the contact pressures, crack initiation and crack propagation.
2. The specific changes to the design of posterior crowns that could be effective in reducing the incidence of failure. The research into this aspect should include the stress distributions throughout the crown and the tooth. An added aspect of this

direction would be to investigate the more complex design of a ceramic onlay with emphasis on the more stress distribution associated with cusp capping where capping is used to prevent fracture of the tooth.

3. The effect of different antagonist materials and their geometry as a guide to case selection for these types of crowns.
4. The effect of surface strengthening by ion exchange in providing added resistance to fracture initiation.
5. The influence of different luting systems and their film thicknesses on the overall ability of the crown to resist failure. This would include aspects of adhesion to tooth structure or core material.
6. The optical effects of bringing the core material closer to the restoration surface in aesthetically sensitive areas such as the occlusal surfaces of molars and premolars. and how they may be modified.
7. The effect of different core materials providing support for the crown. The specific aspects needed to be researched are the type of tooth and its occlusal role with respect to direction of load and overall bulk of the core material used, and the Young's modulus of the support material. For example it would be expected that gold would provide a stiffer support platform than a glass ionomer core. Glass ionomer has been advocated by various manufacturer's for this support role.

Appendix I: ISO Standards for the testing of Dental Porcelain.

ISO 6872: 1995(E)

Part 4: Types, classes and their identification.

Dental ceramics are designated in two types. Type I includes ceramic products which are provided as a powder: type II includes all other forms of ceramic product. Ceramics shall be divided into classes according to their intended use.

Type II, class 1 ceramics are used for the fabrication of the support structure for crowns veneers, inlays and onlays, thus referring to materials which are intended to be layered with material from one or more of type I ceramics, classes 2 to 8. Type II, class 2 ceramics are used for the fabrication of veneers, inlays and onlays.

8.3.2 Biaxial Flexure Test

8.3.2.1 Apparatus

8.3.2.1.1 Equipment for the production, by grinding, of flat parallel sided specimens.

8.3.2.1.2 Biaxial flexural strength testing machine capable of a rate of crosshead speed of (1 ± 0.5) mm/min. For the support of the test specimen, three hardened steel balls with a diameter of (3.2 ± 0.5) mm, positioned 120° apart on a support circle with a diameter of 10 to 12 mm, shall be provided. The sample shall be placed concentrically on these supports and the load shall be applied with a flat punch with a diameter of 1.2 to 1.6 mm at the centre of the specimen.

8.3.2.2 Preparation of the specimens.

The specimen dimensions are reported to range from 12 to 16 mm diameter with 1.2 to 2 mm thickness.

8.3.2.4 Calculation and assessment of results.

Calculate the biaxial flexural strength for each specimen from the following equation:

$$S = -0.238(7P(X - Y))/d^2$$

where

S is the maximum centre tensile stress in megapascals;

P is the total load causing fracture, in Newtons;

$$X = (1 + \nu) \ln(r_2/r_3)^2 + [(1 - \nu)/2](r_2/r_3)^2$$

$$Y = (1 + \nu) \left[1 + \ln(r_1/r_3)^2 \right] + (1 - \nu)(r_1/r_3)^2$$

in which

ν is Poisson's ratio. If the value for the ceramic concerned is not known, use
Poisson's ratio = 0.25;

r_1 is the radius of the support circle, in millimetres;

r_2 is the radius of the loaded area, in millimetres;

r_3 is the radius of the specimen, in millimetres;

d is the specimen thickness at fracture origin, in millimetres.

Appendix II: Manufacturermins Instructions for the use of In-Ceram, Vitadur Alpha.

Table 1 Construction Schedule for In-Ceram Crowns

Step	In-Ceram® Crown Construction
1	The Master Die is constructed from the clinical master impression
2	After sectioning the die is coated with three layers of In-Ceram Interspace Varnish®
3	An impression of the coated die is made with polyvinyl siloxane impression material
4	The duplicate impression is poured with In-Ceram Special Plaster® and allowed to set for 2 hours. The margin of the die is marked with a fireproof china pencil.
5	While the plaster is setting the In-Ceram Alumina “Slip” is prepared by adding 38 grams of the In-Ceram Alumina powder to 5 millilitres of the water based In-Ceram Fluid. Ultrasonic vibration and vacuum is used to facilitate complete wetting of the powder particles
6	The “Slip” is carefully painted onto the plaster die using a small synthetic brush and slow strokes. The process is done steadily to allow the plaster die to absorb the water and to compact the particles, which are drawn to the die. Figure 3.5
7	The built up “Slip” can be trimmed with a sharp knife prior to firing
8	The slip build-up for the coping that will become the core is now placed in the Incerammat® furnace and the first firing cycle is started. This takes approximately 10 hours and the sintering temperature is 1120° C.
9	After the furnace has cooled below 400° C the furnace is opened and the die and coping removed. Figure 3.6

10	The coping is carefully inspected to check that no flash excesses protrude past the margin and it is then tried on the original master die from which the interspace varnish has now been removed.
11	The water based slurry of powdered lanthana based glass is applied to the outside of the coping. This is then placed on a 95% Platinum / 5% Gold alloy foil and put onto the firing tray of the Incerammat® furnace and fired for 4 to 6 hours at 1100° C. Figure 3.7
12	Following cooling the excess glass (figure 3.8) is removed from the coping using diamond burs and alumina particle air abrasion at 5 bar.
13	The coping is then fired in a standard dental vacuum porcelain furnace at approximately 960° C for a further 30 minutes. Excess glass pools on the surface and is removed by air abrasion as before.
14	The coping is then returned to the master model (figure 3.9) and the first layers of dentine and enamel porcelains from the Vitadur Alpha® range are added to build the final shape and colour into the crown. This first build-up is fired in a vacuum at 960° C. Figures 3.10 a & b demonstrate the close unity of the join between the two layers.
15	A second firing takes place after additional porcelain powders are added to correct minor shape changes that occur during the firing shrinkage of the first bake. This firing is usually at 950° C and again under vacuum.
16	Final adjustments are made using diamond burs and then a glaze is added. This is baked in air at 940° C.

Table 2 The firing schedule for In-Ceram® and Vitadur Alpha®.

	Drying & First Ramp Up		Second Ramp Up		Hold Temp		Cool Down	
In-Ceram Slip Fire	120°	6h	1120°	2h	1120°	2h	Overnight	
In-Ceram Glass Fire	Not required		1100°	30 min	1100°	4h	Overnight	
	Heat Soak		Ramp up & Vacuum		Hold Temp		Cool Down	
In-Ceram post SandBlast	600°	6min	960°	6min	960°	1min	Amb	15mi n
Vitadur Alpha 1st Main Fire	600°	6min	960°	6min	960°	1min	Amb	15mi n
Vitadur Alpha 2nd Fire	600°	6min	950°	6min	950°	1min	Amb	15mi n
Vitadur Alpha Correction Fire	600°	6min	940°	6min	940°	1min	Amb	15mi n
	Heat Soak		Ramp up, No Vacuum		Hold Temp		Cool Down	
740 Delta Chrome Glaze Fire	600°	6min	940°	6min	940°	1min	Amb	15mi n

Note: All initial temperature ramp-ups for firing the In-Ceram® core in the Inceramat® are presumed to start from room temperature, as the ceramic is normally handled in the hand. All times after the overnight glass firing are in minutes and temperatures in ° C.

The furnaces used for the construction of all crowns and discs appear in the figure below.



Figure App 1 The left furnace is the Vita Inceramat furnace designed for sinter firing the InCeram core alumina and then to refire the core to infuse the Lanthana based glass. This furnace does not have a vacuum facility. The furnace on the right is a Vita Vacumat 200 which is designed to bake the veneering porcelain onto the InCeram core. This furnace provides a vacuum condition for parts of the firing cycle.

BIBLIOGRAPHY

Abbate MF Tjan AHL and Fox WM. Comparison of the marginal fit of various ceramic crown systems. *J. Prosthet. Dent.* 1989; 61: 527-531.

Aboush Y.E.Y. and Jenkins C.B.G. Tensile strength of enamel-resin-metal joints. *J. Prosthet. Dent.* 1989; 61: 688 - 694.

Anstis GR, Chantikul P, Lawn BR, and Marshall DB. A critical evaluation of indentation techniques for measuring fracture toughness: I, Direct crack measurements. *J. Am. Ceram Soc.* 1981; 64: 533-538.

Anusavice K. J. Shen C. and Lee R.B. Strengthening of Feldspathic Porcelain by ion exchange and tempering. *J. Dent. Res.* 1992; 71: 1134-1138

Anusavice K.J. and Hojjatie B Influence of Incisal Length of Ceramic and Loading Orientation on Stress Distribution in Ceramic Crowns. *J. Dent. Res.* 1988; 67: 1371 - 1375.

Anusavice K.J. and Hojjatie B. Effect of thermal tempering on Strength and Crack propagation Behaviour of Feldspathic Porcelains. *J. Dent. Res.* 1991b; 70: 1009-1013.

Anusavice K.J. and Hojjatie B. Influence of incisal length of ceramic and loading orientation on stress distribution in ceramic crowns. *J. Dent. Res.* 1988; 67: 1371 - 1375.

Anusavice K.J. Gray A. and Shen C. Crack growth in air-tempered porcelain: influence of initial flaw size. *J. Dent Res.* 1989 ; 68 : 959 Abstr. No. 743.

Anusavice K.J. Gray A. and Shen C. Influence of initial flaw size on crack growth in air-tempered porcelain. *J. Dent Res.* 1991a ; 70 : 131-136.

Anusavice KJ, De Rijk WG. Performance of dental biomaterials: conference report. *Dent Mater* 1990; 6:69-72.

Anusavice KJ, Hojjatie B. Influence of Incisal Length of Ceramic and Loading Orientation on Stress Distribution in Ceramic Crowns. *J Dent Res* 1988;67:1371-1375.

Anusavice KJ, Lee RB. Effect of firing temperature and water exposure on crack propagation in unglazed porcelain. *J Dent Res* 1989; 68:6:1075-1081.

Aranda R. and Barghi N. An evaluation of four techniques for condensation of three opaque porcelains. *J. Prosthet. Dent.* 1988; 60: 29-31.

Asaoka K. and Tesk JA Visco-elastic deformation of dental porcelain and porcelain-metal compatibility. *Dent. Mater.* 1991; 7: 30-35.

Asaoka K. Yoshida K. and Sakamaki K. Effect of transient stress on acoustic emission behaviour during firing of dental porcelain. *J. Mater. Sci.* 1992; 27: 3118-3122

Ban S. and Anusavice K.J. Influence of test method on failure stress of brittle dental materials. *J. Dent. Res.* 1990; 69: 1791-1799.

Banks R.G. Conservative posterior ceramic restorations: A literature review. *J. Prosthet. Dent.* 1990 ; 63 : 619 - 626.

- Barreiro MM, Riesgo O and Vicente EE. Phase identification in dental porcelains for ceramo-metallic restorations. *Dent. Mater.* 1989; 5: 51-57.
- Becher PF and Swain MV Grain-size-dependent transformation behaviour in polycrystalline tetragonal zirconia. *J. Am. Ceram. Soc.* 1992; 75: 493-502.
- Bendeich P, Payten W. 3-Dimensional Shape Optimization for Ceramic Reliability Using a Heuristic Approach. Submitted to *Finite Elements Analysis Design*, 2001.
- Binns D. The chemical and physical properties of dental porcelain. *Proc. 1st Int. Symposium on Ceramics*. Chicago: Quintessence Publ. Co. Inc, 1983 ; 41 - 82.
- Broughton A.M. A survey on the use of resin bonded restorations by members of the Australian Prosthodontic Society. *Aust. Prosthodont. J.* 1990; 4(Suppl.) 27-33.
- Brukl CE and Ocampo RR Compressive strength of a new foil and porcelain-fused-to-metal crowns. *J. Prosthet. Dent.* 1987; 57: 404 - 410
- Budworth DW. An introduction to ceramic science. Pergamon Press. 1970: 235-237.
- Campbell S.D. and Sozio R.B. Evaluation of fit and strength of an all ceramic fixed partial denture. *J. Prosthet. Dent.* 1988; 59: 301-306.
- Carrier DD and Kelly JR. In-Ceram failure behaviour as influenced by residual infiltration glass. *J. Dent. Res.* 1994; 73: 191 Abstr No. 719.
- Chan C and Weber H. Plaque retention on teeth restored with full-ceramic crowns: A comparative study.
- Chantikul P, Anstis GR, Lawn BR, Marshall DB. A critical evaluation of indentation techniques for measuring fracture toughness: II, strength method. *J Am Ceram Soc* 1981; 64: 9:539-543.
- Chudoba T, Schwarzer N, Richter F, Beck U: "Determination of mechanical film properties of a bilayer system due to elastic indentation measurements with a spherical indenter", proceedings of the ICMCTF 2000, San Diego, USA, April 2000, 366 – 372, in addition: *Thin Solid Films* 377 – 378 (2000b) 366 - 372
- Chudoba T, Schwarzer N, Richter F: "Determination of Elastic Properties of Thin Films by Indentation Measurements with a Spherical Indenter", *J. of Surface & Coatings Technology* 127 (2000a) 9-17
- Chudoba T, Schwarzer N, Richter F: "New Possibilities of Mechanical Surface Characterization with Spherical Indenters by Comparison of Experimental and Theoretical Results", San Diego Conference ICMCTF 1999, Metallurgical Coatings and Thin Films Vol. II, Elsevier, pp. 284-289 and *Thin Solid Films* 355-356 (1999), 284-289
- Claus H. Vita In-Ceram, a new system for producing aluminium oxide crown and bridge substructures. *Quintessenz Zahntechnik* 1990; 16: 1-11.
- Combe EC. Notes on Dental Materials. 5th ed. Churchill Livingstone, 1981:12.
- Cook R. Concepts and Applications of Finite Element Analysis. New York: John Wiley and Sons, 1974:311-353.
- Craig RG, Peyton FA and Johnson DW Compressive properties of enamel, dental cements, and gold. *J. Dent. Res.* 1961; 40: 936-945.

- Davidson CL, Van Zeghbroeck L. and Feilzer A.J. Destructive stresses in adhesive luting cements. *J. Dent. Res.* 1991; 70: 880-882.
- Davis JB, Cao HC, Bao G and Evans AG. The Fracture Energy of Interfaces: An Elastic Indentation Technique. *Acta. Metall. Mater.* 1991; 39: 1019-1024.
- Dehof P.H. and Anusavice K.J. Tempering stresses in feldspathic porcelain: *J. Dent. Res.* 1989; 68:134-138
- Dehoff P.H. and Anusavice K.J. Analysis of tempering stresses in bilayered porcelain discs. *J. Dent. Res.* 1992; 71: 1139-1144.
- DeLong R, Sasik C, Pintado MR and Douglas WH. The wear of enamel when opposed by ceramic systems. *Dent. Mater.* 1989; 5: 266-271.
- Denry IL and Rosenstiel SF. Flexural strength and fracture toughness of Dicor glass-ceramic after embedment modification. *J. Dent. Res.* 1993; 72: 572 - 576.
- Denry IL. Recent Advances in Ceramics for Dentistry. *Crit Rev Oral Biol Med* 1996; 7: 134-143.
- Dérand T. Analysis of stresses in loaded models of porcelain crowns. *Odont. Rev.* 1974; 25: 189-206.
- Dérand T. Stress analysis of cemented or resin-bonded loaded Porcelain Inlays. *Dent. Mater.* 1991; 7: 21-24.
- Dickinson A.J.G. Moore B.K. Harris R.K. and Dykema R.W. A comparative study of the strength of aluminous porcelain and all-ceramic crowns. *J. Prosthet. Dent.* 1989; 61: 297 - 304.
- Dictionary of scientific and technical terms 1990. 4th ed. McGraw Hill. Ed. Parker SP.
- Dietschi D. Maeder M. Meyer J-M. and Holz J. In vitro resistance to fracture of porcelain inlays bonded to tooth. *Quint. Int.* 1990 ; 21 : 823-831.
- Dinsdale A, Cramm J and Wilkerson WT. Mechanical strength of ceramic tableware. *Trans Br Ceram Soc.* 1967; 66: 367 - 404
- Dong D.R Lautenschlager EP and Gilbert J.L. The effect of method and rate of loading on shear bond strength tests. *J. Dent Res.* 1989; 68: 249 Abstr. No. 540.
- Doremus R. H. Strengthening of glass. 1973 In: *Glass Science*, R.H. Doremus, Ed., New York: John Wiley and Sons, Inc. pp 310-315.
- Drummond J.L., Novickas D. and Lenke J.W. Physiological aging of an all-ceramic restorative material. *Dent. Mater* 1991; 7: 133-137.
- Dunn B. Levy MN and Reisbick M.H. Improving the fracture resistance of dental ceramic. *J. Dent. Res.* 1977; 56: 1209-1213.
- Edwards M.R. Jacobsen P.H. and Williams G.J. The three-point bend test for the evaluation of dental porcelains. *J. Dent. Res.* 1983; 62: 1086-1088.
- Evans AG and Charles EA. Fracture toughness determination by indentation. *J. Am. Ceram. Soc.* 1976; 59:371-372.

Evans AG and Hutchinson JW. Effects of non-planarity on the mixed mode of fracture resistance of biomaterial interfaces. *Acta Metall* 1989; 37: 909 - 916

Evans AG and Marshall DB. (1980) Wear mechanisms in ceramics. In: Rigney DA, editor. *Fundamentals of friction and wear of materials*. American Society for Metals, 439-453.

Evans AG. *J. Am Ceram. Soc.* 1990; 73: 187.

Ewalds HL and Wanhill RJH, (1984) *Fracture Mechanics*. London: Edward Arnold.

Fairhurst C.W. Hashinger DT and Twiggs SW The effect of thermal history on porcelain expansion behaviour. *J. Dent. Res.* 1989 ; 68 : 1313 - 1315

Fan. PL. Recent advances in all-ceramic crowns. In: *The dental annual 1988*. Ed: Derrick DD. Wright Publications Inc. 1988; 105-109.

Farah J.W. Craig R.G. Eden G.T. and Grossman D.G. Two-dimensional photoelastic simulation of a castable ceramic fixed partial denture. *J. Prosthet. Dent.* 1988; 59: 8-12.

Faulkner A, Tang KC, Schwarzer N, Arnell RD, Richter F: "Comparison between an Elastic-Perfectly Plastic FE Model and a Purely Elastic Analytical Model for a Spherical Indenter on a Layered Substrate", *Thin Solid Films* 300 (1997) 177

Field JS and Swain MV. A simple predictive model for spherical indentation. *J. Mater. Res.* 1993; 8: 297-306.

Fields H.W. Proffit W.R. Case J.C. and Vig K.W.L. Variables affecting measurements of vertical occlusal force. *J. Dent. Res.* 1986; 65: 135-138.

Fischer-Cripps AC *Introduction to Contact Mechanics*. 1998 Frederick F. Ling Series Ed. Springer-Verlag; New York, Berlin, Heidelberg.

Friedlander L. Munoz C. Goodacre C. and Moore K. Effect of tooth preparation design on breaking strength of Dicor crowns. *J. Dent Res.* 1989 ; 68 : 395 Abstr. No. 1707.

G+D Computing. *Using Strand7*. Sydney: G+D Computing, 1999:1-220

Gehrke E, Ullner Ch and Hahnert M. Fatigue limit and crack arrest in alkali-containing silicate glasses. *J. Mater. Sci.* 1991; 26: 5445-5455.

Giordano RA, Campbell S and Pober R. Flexural strength of feldspathic porcelain treated with ion exchange, overglaze, and polishing. *J. Prosthet. Dent.* 1994; 71: 468-72.

Glaser. C.G. and Nagy W.W. Restoration of canine disocclusion by using etched porcelain onlays. *J. Prosthet. Dent.* 1991; 65: 338-334.

Grossman DG. Cast Glass Ceramics. *Dent. Clin. Nth. Am.* 1985; 29: 725-739.

Gupta PK and Jubb NJ. Post-Indentation slow growth of radial cracks in glasses. *J. Am. Ceram. Soc.* 1981; 64: C112 - C114.

Guyer SE et al. A compressive strength study of an all-ceramic crown. *J. Prosthet. Dent.* 1985; 53: 301-303.

Hammad IA Goodkind RJ and Gerberich W.W. A shear test for the bond strength of ceramometals. *J. Prosthet. Dent.* 1987; 58: 431-437

- Hassan R, Caputo AA and Bunshah RF. Fracture toughness of human enamel. *J. Dent. Res.* 1981; 60: 820-827
- Hasselman DPH and Fulath RM. Proposed fracture theory of a dispersion-strengthened glass matrix. *J Am Ceram Soc.* 1966; 49: 68-72.
- He MY and Hutchinson. Crack Deflection at an interface between dissimilar elastic materials. *Int. J. Solid Structures* 1989; 25:1053 - 1076.
- He MY and Hutchinson. Kinking of a crack out of an interface. *J Appl. Mech (Trans ASME)* 1989; 56: 270 - 278
- Highton R. Caputo AA and Matyas J. A photoelastic study of stresses on porcelain laminate preparations. *J. Prosthet. Dent.* 1987; 58: 157-161
- Hojjatie B and Anusavice KJ. Effects of initial temperature and tempering medium on thermal tempering of dental porcelains. *J. Dent. Res.* 1993; 72: 566 - 571.
- Hondrum SO A review of the strength properties of Dental Ceramics. *J. Prosthet. Dent.* 1992; 67: 859 – 864.
- Hondrum SO and O'Brien WJ. The strength of Alumina and Magnesia Core Crowns. *Int. J. Prosthodont.* 1988; 1: 67-72.
- Hornberger H Strength Microstructure relationships in a Dental Alumina Glass Composite. PhD Thesis 1995. University of Birmingham, School of Dentistry – Biomaterials Unit.
- Hu XZ, Lutz EH and Swain MV. Crack-tip-bridging stresses in ceramic materials. *J. Am. Ceram. Soc.* 1991; 74: 1828-1832.
- Ironside JG and Styles GT. Core framework design to change resistance to crack initiation. *J. Dent. Res.* 1995b; 74: 522, Abstr. No. 975.
- Ironside JG and Watson TF. Damage Following Finishing Procedures: A Confocal Microscope View. *J. Dent. Res.* 1995c; 74: 755, Abstr. No. 78.
- Ironside JG Proos K and Swain MV. Finite element analysis of bilaminar dental ceramic discs. To be Published 2001
- Ironside JG Light Transmission of a Ceramic Core Material used in Fixed Prosthodontics. *Quint. Dent Tech.* 1993; 16: 103 -106
- Ironside JG. The effect of porosity on the flexural strength of In-Ceram. *J. Dent. Res.* 1995a; 74: 522, Abstr. No. 973.
- Ironside JG The In-Ceram metal-free ceramic system for Fixed Prosthodontics. *Australian Prosthodontic Journal* 1993; 7: 55 – 61.
- Jamting AK, Swain MV, Bell J, Schwarzer N: Investigation of the Elastic Modulus of Thin Films Using Simple Biaxial Bending Techniques, *Proceedings of the International Conference on Metallurgical Coatings and Thin Films*, 21.-25. 04. 1997, San Diego, Kalifornien, USA, 304 – 309
- Jones DW, Rizkalla AS, King HW and Sutow EJ. Fracture toughness and dynamic modulus of tetrasilicic-micaglass-ceramic. *J. Can Ceram Soc* 1988a; 57: 39-46.

Jones DW, Rizkalla AS, Sutow EJ and King HW. Indentation fracture toughness and dynamic Young's modulus of ceramic biomaterials. *Mater Sci E* 1988b; A105/106: 207-213

Jones DW: The strength and strengthening mechanisms of dental ceramics, in McLean JW (Ed): Dental Ceramics. Proceedings of the First International Symposium on Ceramics. Chicago, Quintessence Publ. Co. Inc. 1983, p 69.

Kase H.R, Tesk JA and Case E.D. Elastic constants of two dental porcelains. *J. Mater. Sci.* 1985; 20: 524-531.

Kelly JR Campbell S.D. and Bowen H.K. Fracture-surface analysis of dental ceramics. *J. Prosthet. Dent.* 1989; 62: 536-541

Kelly JR, Giordano R, Pober R, Clima MJ. Fracture surface analysis of dental ceramics: clinically failed restorations. *Int Prosthodont J* 1990; 3: 430-440.

Kelly JR. Perspectives on Strength. *Dent Mater* 1995;11:103-110.

Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. *J. Prosthet. Dent.* 1999; 81: 652-661.

Kern M and Thompson VP. Sandblasting and silica coating of a glass-infiltrated alumina ceramic: Volume loss, morphology, and changes in the surface composition. *J. Prosthet. Dent.* 1994; 71: 453-61.

Korioth TWP, Versluis A. Modelling the Mechanical Behaviour of the Jaws and their Related Structures by Finite Element (FE) Analysis. *Crit Rev Oral Biol Med* 1997;8:90-104.

Kvam K. Fracture toughness determination of ceramic and resin bonded dental composites. *Biomater.* 1992; 13: 101- 104.

Lamon J, Evans AG. Statistical analysis of bending strength of brittle solids: a multiaxial fracture problem. *J Am Ceram Soc* 1983; 66:177-182.

Lampe K, Lüthy H and Mörmann WH. Fracture load of all-ceramic computer crowns. In International Symposium on Computer Restorations., Ed W H Mörmann, Quintessence, Berlin, 1996, pp, 466 – 481

Lawn BR and Marshall DB Hardness, toughness, and brittleness: an indentation analysis. *J. Am Ceram Soc* 1979; 62: 347-350.

Lawn BR and Wilshaw TR. Indentation fracture: Principles and Applications. *J. Mater. Sci.* 1975; 10: 1049-1081.

Lawn BR. Fracture of Brittle Solids - Second Edition EA Davis and IM Ward (Eds.) Cambridge Solid State Science Series. Cambridge University Press, 1993.

Lawn BR. Friction processes in Brittle Fracture. I. L. Singer and H. M. Pollock (eds.) Fundamentals of Friction: Macroscopic and Microscopic Processes. Kluwer Academic Publishers 1992; 137-165.

Lewis CF. Testing ceramic fracture toughness. *Mater Eng (Minn)* 1990;10: 31-33.

Llorca J. and Steinbrech RW. Fracture of alumina: an experimental and numerical study. *J. Mater. Sci.* 1991; 26: 6383 - 6390.

- Mackert J.R., Jr. and Evans AL Effect of cooling rate on leucite volume fraction in dental porcelains. *J. Dent. Res.* 1991; 70: 137-139.
- Magne P and Belser U. Esthetic improvements and In Vitro testing of In-Ceram Alumina and Spinell Ceramic. *Int. J. Prosthodont.* 1997; 10: 459 – 466.
- Magne P, Douglas WH. Design Optimization and Evolution of Bonded Ceramics for the Anterior Dentition: A Finite-Element Analysis. *Quintessence Int* 1999;30:661-672.
- Magne P, Douglas WH. Porcelain Veneers: Dentin Bonding Optimization and Biomimetic Recovery of the Crown. *Int J Prosthodont* 1999;12:111-121.
- Magne P, Versluis A, Douglas WH. Effect of Luting Composite Shrinkage and Thermal Loads on the Stress Distribution in Porcelain Laminate Veneers. *J Prosthet Dent* 1999;81:335-344.
- Magne P, Versluis A, Douglas WH. Rationalization of Incisor Shape: Experimental-Numerical Analysis. *J Prosthet Dent* 1999;81:345-355.
- Malament KA and Socransky SS. Survival of Dicor glass-ceramic dental restorations over 14 years: Part 1. Survival of Dicor complete coverage restorations and effect of internal surface etching, tooth position, gender and age. *J. Prosthet. Dent.* 1999; 81: 23 – 32.
- Marquis P. Optimising the strength of all-ceramic jacket crowns. In: *Perspectives in Dental Ceramics. Proceedings of the Fourth International Symposium on Ceramics.* J. D. Preston Ed. Quintessence Publ. Co. Inc. Chicago 1988.
- Marshall D. B. and Lawn B. R. An indentation technique for measuring stresses in tempered glass surfaces. *J. Am. Ceram Soc. - Discussions and Notes.* 1977; 60: 86-87.
- Marshall D. B. and Lawn B. R. Strength degradation of thermally tempered glass plates. *J. Am. Ceram. Soc.* 1978b; 61:21-27.
- Marshall DB and Lawn BR. Residual stress effects in sharp contact cracking. Part 1 Indentation fracture mechanics *J. Mater. Sci.* 1979; 14: 2001-2012.
- Marshall DB. An improved Biaxial Flexure Test for Ceramics. *Ceramic Bulletin* 1980; 59: 551 - 553.
- Mc Lean JW. *Proceedings of the First International Symposium on Dental Ceramics.* McLean JW, ed Chicago: Quintessence, 1983;31.
- McCabe J.F. Carrick T.E. Chadwick R.G. and Walls A.W.G. Alternative approaches to evaluating the fatigue characteristics of materials. *Dent. Mater.* 1990; 6: 24-28.
- McLean JW. High strength ceramics. *Quintessence Int* 1987;18:2:97-106.
- McLean J.W. and Kedge MI High Strength Ceramics. *Quint. Int.* 1987 ; 18 : 97 -106.
- McLean J.W. The Art and Science of Dental Ceramics. *Operative Dent.* 1991; 16: 149-156.
- McLean J.W. *The Art and Science of Dental Ceramics. Volume 1* Quintessence Publ. Co. Chicago. 1979; 1: 19-21.
- McLean JW, Hughes TH. The reinforcement of dental porcelain with ceramic oxides. *Br Dent J* 1965; 9:251-267.

- Mecholsky JJ, Jr. Fractography: Determining the sites of fracture initiation. *Dent. Mater.* 1995; 11:113-116.
- Mecholsky JJ, Jr. Fracture mechanics principles. *Dent. Mater.* 1995; 11:111-112.
- Mencík J. *Mechanics of Components with Treated or Coated Surfaces*. Gladwell GML Ed. Kluwer Academic Publishers. Dordrecht / Boston / London. 1996.
- Messer PF, Piddock V, Lloyd CH. The strength of dental ceramics . *J Dent* 1991;19:51-55.
- Meuller HJ. Fracture toughness and fractography of dental ceramics. *Cells and materials*. 1991; 1: 265-278.
- Morena R, Lockwood PE and Fairhurst CW. Fracture toughness of commercial dental porcelains. *Dent. Mater.* 1988; 2: 58-62.
- Morena R. et al. Fatigue of dental ceramics in a simulated oral environment. *J. Dent. Res.* 1986; 65: 993-997.
- Naylor et al. The effect of surface treatment on the Knoop hardness of Dicor. *Int. J. Prosthodont* 1991; 4: 147-151.
- Neiva G, Yaman P, Dennison J.B, Razzoog M.E. and Lang BR Resistance to Fracture of Three All-Ceramic Systems. *J. Esthet. Dent.* 1998; 10: 60-66.
- Outwater GR and Gerry PD. A new technique for determination of fracture toughness. *J Am Ceram Soc* 1966;26:102-111.
- Owen DRJ and Fawkes AJ (1983). *Engineering fracture mechanics: Numerical methods and applications*. Swansea: Pineridge Press.
- Papavasiliou G, Tripodakis APD, Kamposiora P, Strub JR, Bayne SC. Finite Element Analysis of Ceramic Abutment-Restoration Combinations for Osseointegrated Implants. *Int J Prosthodont* 1996;9:254-260.
- Petrovic JJ and Stout MG. Fracture of Al_2O_3 in Combined Tension/Torsion: II, Weibull Theory. *J. Am. Ceram Soc.* 1981; 64: 661-666
- Philp G.K. and Brukl CE Compressive strengths of conventional, twin foil, and all-ceramic crowns. *J. Prosthet. Dent.* 1984; 52: 215-220.
- Pratt R.C. Burgess J.O. Schwartz RS and Smith J.H. Evaluation of bond strength of six porcelain repair systems. *J. Prosthet. Dent.* 1989; 62: 11-13
- Pretipino V and Ingber A. Esthetic high-strength implant abutments. Part 1. *J Esthet. Dent.* 1993: 29 – 35.
- Probster L. Compressive Strength of Two Modern All-Ceramic Crowns. *Int. J. Prosthodont.* 1992; 5: 409 - 414.
- Raimondo R.L. Richardson JT and Wiedner B. Polished versus autoglazed dental porcelain. *J. Prosthet. Dent.* 1990 ; 64 : 553 - 557.
- Rasmussen ST, Patchin RE, Scott DB and Heuer AH. Fracture properties of human enamel and dentin. *J. Dent. Res.* 1976; 55: 154-164.

- Rhee Y-W, Kim H-W, Deng Y and Lawn BR. Contact-induced Damage in Ceramic Coatings on Compliant Substrates: Fracture Mechanics and Design. *J. Am. Ceram. Soc.* 2001; 84: 1066-72
- Richards MW and Kelly JR. Indentation-Strength of Unpressed and Pressed Empress Discs. *J. Dent. Res.* 1994; 73: 191 Abstr. No. 717.
- Richter F, Chudoba T, Schwarzer N, Hecht G: „Neue Möglichkeiten zur Charakterisierung dünner Schichten mit Indentermethoden - Novel Possibilities for Thin Film Characterisation Using Indentation Methods”, *Materialwissenschaften und Werkstofftechnik*, accepted 4.10.2000
- Ridlon S. Modeling Guidelines. In: Meyer C (Ed). *Finite Element Idealization – for Linear Elastic Static and Dynamic Analysis of Structures in Engineering Practice*. New York: American Society of Civil Engineers, 1987:212-271.
- Ritter JE. Predicting lifetimes of materials and material structures. *Dent. Mater.* 1995; 11: 142-146.
- Rosensteil SF, Porter SS. Apparent fracture toughness of all ceramic crown systems. *J Prosthet Dent* 1989; 62:29-32.
- Rosenstiel S.F. and Porter SS Apparent fracture toughness of all-ceramic crown systems. *J. Prosthet. Dent.* 1989; 62: 529-532.
- Roulet J.F. and Soderholm K.-J.M. Variables influencing the bond strength of ceramic-resin interfaces. *J. Dent Res.* 1991 ; 70 : 434 Abstr. No. 1348.
- Sanders G, Swain MV. Mechanical property and microstructural observations for some silicon carbide reinforced alumina composites. *Materials forum* 1990;14:60-69.
- Scherrer SS, De Rijk WG and Belser UC. Fracture resistance of three all ceramic crown systems compared to extracted teeth. *J. Dent. Res.* 1994; 73: 190 Abstr No. 711.
- Schwarzer N, Chudoba T, Billep D, Richter F: “Investigation of coating substrate compounds using inclined spherical indentation”, *J. of Surface & Coatings Technology* 116 – 119 (1999b) 244-252
- Schwarzer N, Hermann I, Chudoba T, Richter F: “Contact Modelling in the Vicinity of an Edge”, *Proceedings of the ICMCTF 2001, San Diego, USA, April/Mai 2001a*, submitted
- Schwarzer N, Heuer D, Chudoba T: “Application of modern approaches in mechanics to adhesion problems in dentistry”, *proceedings of the EURADH 2000, Lyon, France, September 2000b*, Edition SFV, 19 rue du Renard, 75004 Paris, 377-382
- Schwarzer N, Richter F, Hecht G: “Elastic Field in a Coated Half Space under Hertzian pressure distribution“, *J. of Surface & Coatings Technology* 114 (1999a) 292-304
- Schwarzer N, Richter F, Michel B: “Penny shaped interface crack under uniform pressure and shear loading”, in “Modelling and Simulation Based Engineering”, Vol. II, Ed. S. N. Atluri, P. E. O'Donoghue, Atlanta, USA (1998b), Tech Science Press
- Schwarzer N, Richter F: "A Simple Biaxial Bending Technique for Coated Materials - Theory and Application", *proceedings to the workshop "Mechanical Behaviour of PVD Coated Materials"*, 13.-17.10.1997 in Holzhau, Germany, edited by H. Oettel, S. Hogmark, J. v. Stebut, published in "*Freiburger Forschungshefte*", B 287, 1998a, pp. 93 - 100

Schwarzer N, Richter F: "Adhesion Modelling in Layered Materials Using Analytical Solutions of Crack Problems", proceedings of the EURADH 2000, Lyon, France, September 2000a, Edition SFV, 19 rue du Renard, 75004 Paris, 586-591

Schwarzer N: "Coating Design due to Analytical Modelling of Mechanical Contact Problems on Multilayer Systems", proceedings of the ICMCTF 2000, San Diego, USA, April 2000b, 397 - 402, in addition: Surface and Coatings Technology 133 -134 (2000) 397 - 402

Schwarzer N: "Arbitrary load distribution on a layered half space", ASME Journal of Tribology, Vol. 122, No. 4, October 2000a, 672 - 681

Schwarzer N: „Arbitrary Load Distribution on Quarter and Eighth Spaces", Int. J. of Solids and Structures, submitted 2001b.

Seghi RR, Crispin BC and Mito W. The effect on ion exchange on the flexural strength of feldspathic porcelains. Int. J. Prosthodont. 1990; 3: 130-134.

Seghi RR. Rosenstiel S.F. and Bauer P. Abrasion of human enamel by different Dental Ceramics in vitro. J. Dent. Res. 1991; 70: 221-225.

Seghi RR. Sorensen JA Engelman M.J. Roumanas E. and Torres T.J. Flexural strength of new ceramic materials. J. Dent. Res. 1990; 69: 299 Abstr. No. 1521.

Seghi RR. Sorensen JA Relative flexural strength of six new ceramic materials. Int J Prosthodont 1995; 8: 239-246.

Sorensen JA, Torres SK, Kang SK and Avera SP Marginal fidelity of ceramic crowns with different margin designs. J. Dent. Res. 1990; 69: 279 Abstr. No. 1365.

Southan DE and Jorgensen K.D. An appropriate mechanical test for dental porcelain. Aust. Dent. J. 1973; 18: 246-250.

Southan DE and Jorgensen K.D. An explanation for the occurrence of internal faults in porcelain jacket crowns. Aust. Dent. J. 1973; 18: 246-250.

Southan DE Effect of surface injury on chemically strengthened dental porcelain. Quint. Int 1987; 18: 575-580.

Southan DE Factors affecting the translucency of dental porcelain. Quint. Int 1987; 18: 197-202.

Southan DE Optical density-strength relationships in dental porcelain. Quint. Int 1987; 18: 261-263.

Southan DE Strengthening modern dental porcelain by ion exchange. Aust. Dent. J. 1970; 15: 507-510

Southan DE The development and characteristics of dental porcelain. Aust. Dent. J. 1970; 15: 103-107

Swain M V. Strategies for strengthening and toughening very hard materials. J. Hard. Mater. 1991; 2: 139-154.

Swain MV. Role of Microstructure on the Abrasive and Erosive Wear of Alumina Ceramics. 1994. Dept. of Mechanical Engineering. University of Sydney, Sydney NSW Australia 2006.

Swanson PL, Fairbanks CJ, Lawn BR, Mai Y-W and Hockey BJ. Crack-Interface grain bridging as a Fracture Resistance Mechanism in Ceramics. *J. Am. Ceram. Soc.* 1987; 70: 279-89.

Tesk JA, Anusavice KJ. Summary of Conference on Design of Dental Prostheses. *Dent Mater* 1988;4:49-50.

Twiggs SW Searle JR Ringle RD and Fairhurst CW A rapid heating and cooling rate dilatometer for measuring thermal expansion in dental porcelain. *J. Dent. Res.* 1989 ; 68 : 1316 - 1318

Wachtman JB, Capps W and Mandel J. Biaxial flexure tests of ceramic substrates. *J. of Mater. JMLSA* 1972; 7: 188-194.

Wändstrand O, Schwarzer N, Chudoba T, Kassman-Rudiphi Å: "Load-carrying capacity of Ni-plated media in spherical indentation: experimental and theoretical results", *J. of Surface and Coatings Technology*, submitted 2001

Wassenaar P. Flexural strength of new ceramic materials. 1991. Personal communication.

Wassenaar P, Cheng IY. Fracture properties of dental ceramics IADR Abstracts 1991;15; 9:32 .

Wassenaar P. The new porcelains - are they any better? *Aust. Prosthodont. J.* 1990; 4(Suppl.) 19-25.

Wiley MG. Effects of porcelain on occluding surfaces of restored teeth. *J. Prosthet. Dent.* 1989; 61: 133-137.

Wohlwend A, Strub JR and Scharer P. Metal-ceramic and all-porcelain restorations: Current considerations. *Int. J. Prosthodont.* 1989; 2: 13-26.

Wolf WD Francis LF Lin C-P and Douglas WH. Melt-Infiltration processing and fracture toughness of alumina-glass dental composites. *J. Am. Ceram. Soc.* 1993; 76: 2691-94.

Yoshinari M and Derand T. Fracture Strength of All-Ceramic Crowns. *Int. J. Prosthodont.* 1994; 7: 329 – 338.