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Theoretical Exploratory Investigation On Reliability Of Advanced Ceramics By Discrete Element Simulation

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THEORETICAL EXPLORATORY INVESTIGATION ON RELIABILITY OF ADVANCED CERAMICS BY DISCRETE ELEMENT SIMULATION

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Ana Laura Quezada Lara

2010
Dedication

The research done is dedicated to my family and friends who have been there for me in all the steps of my education. Also the support and faith the UTEP faculty has on me since the first day I started attending. I truly appreciate everyone that has helped me fulfill this project.
THEORETICAL EXPLORATORY INVESTIGATION ON RELIABILITY OF ADVANCED CERAMICS BY DISCRETE ELEMENT SIMULATION

by

ANA LAURA QUEZADA LARA, BS

THESIS

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I would like to extend my most sincere appreciation and gratitude to Dr. Zhang for all the support given during the thesis period. She has been a great mentor and has helped me discover new areas of research. The trust given by her since the beginning has been unconditional and the experience of doing this research with her has been great. I am thankful to the entire Industrial Engineering faculty who has helped me.
Abstract

The increasing application of silicon nitride in biomedical and other engineering fields has elevated the necessity to understand its reliability. Due to the complexity of producing pure material researchers have been analyzing the behavior of the material with flaws. In this thesis several scenarios are simulated with the support of PFC2D to analyze microcrack propagation depending on the position, quantity and size of the voids to understand the effect each of the cases have on the material. A four point bending test was applied to each case twice recording the loading force. Having two runs allows doing a statistical analysis in Minitab using ANOVA to make the proper conclusions based on the p-value.

According to the first case subsurface defects have a significant effect on the loading force, which lead us to simulate several positions with a void closer to the lower surface in the y-axis or x-axis. The position of the void along the y-axis starting closer to the lower wall of the silicon nitride showed a significant effect on the loading force. In contrast with the y-axis, the voids located along the x-axis with a separation from the lower wall of 20 microns did not show any effect on the loading force. A new comparison was made with two voids of different radius, on this case there was no significant effect on the strength of the material with the parameters selected by the user, but it matched the crack initiation from experimental data starting at the void with the bigger radius.

Another case simulated was adding clusters to the silicon nitride which showed a significant improvement on the reliability of the silicon nitride and matched real life sample. The learning experience of using the software to conduct simulations is the accordance it has with real life experiments; it is a good alternative to understand the reliability and the possible failures of a heterogeneous silicon nitride on real life application such as implants, bearings among others.
# Table of Contents

Acknowledgements...........................................................................................................v

Abstract................................................................................................................................vi

Table of Contents................................................................................................................vii

List of Tables .........................................................................................................................x

List of Figures ........................................................................................................................xi

Chapter 1: Introduction ........................................................................................................1

  1.1 Research Objective ......................................................................................................2

Chapter 2: Literature Review ...............................................................................................4

  2.1 Ceramics Properties ....................................................................................................4

  2.1.1 Ceramics areas of development ......................................................................5

  2.1.2 Ceramics reliability ...............................................................................................5

  2.1.3 Ceramics Evolution ...............................................................................................6

Chapter 3: Experimental Procedure ...................................................................................8

  3.1 PFC2D Software ......................................................................................................8

  3.2 Modeling the sample .................................................................................................9

  3.3 Cases Selection .........................................................................................................11

Chapter 4: Case 1. Upper vs. Lower Void ........................................................................13

  4.1 Sample generation ...................................................................................................13

  4.2 Results .....................................................................................................................15

  4.3 Statistical Analysis Case 1 .....................................................................................16

  4.4 Discussion Case 1 ...................................................................................................17

Chapter 5: Case 2. Voids Size ..........................................................................................19

  5.1 Sample Generation ...................................................................................................19

  5.2 Results .....................................................................................................................20

  5.3 Statistical Analysis Case 2 .....................................................................................21

  5.4 Discussion Case 2 ...................................................................................................21

Chapter 6: Case 3. Location ..............................................................................................23

  6.1 Sample generation: y-axis ......................................................................................23

  6.2 Results: y-axis .........................................................................................................25
List of Tables

Table 3.1 Microparameters of Silicon Nitride Ceramics [12] .................................................................10
Table 4.1 Top vs. Bottom Comparison......................................................................................................15
Table 4.2 Top vs. Bottom Comparison Second Run..............................................................................16
Table 5.1 Size comparison ....................................................................................................................20
Table 5.2 Size comparison Second Run..............................................................................................20
Table 6.1 Depth Comparison .................................................................................................................25
Table 6.2 Depth Comparison Second Run.............................................................................................26
Table 6.3 X-axis comparison first run .................................................................................................30
Table 6.4 X-axis comparison second run .............................................................................................30
Table 7.1 Single vs. double void along the y-axis comparison..............................................................34
Table 7.2 Single vs. double void along the y-axis comparison second run ....................................35
Table 7.3 Single vs. double void along the x-axis comparison first run .........................................38
Table 7.4 Single vs. double void along the x-axis comparison second run .........................................38
Table 8.1 Cluster vs. single balls comparison ......................................................................................41
Table 8.2 Cluster vs. single balls comparison second run ....................................................................41
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 3.1</td>
<td>Particle Properties</td>
<td>8</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Sample Generation</td>
<td>9</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Four Point Bending Test</td>
<td>11</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Void position on the lower and upper surface</td>
<td>13</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Samples before testing Upper Wall Void (left) and Lower Wall Void (right)</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>First cracks: upper void (left) and lower void (right)</td>
<td>14</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Samples after failure: Upper (right) and Lower (up)</td>
<td>15</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Crack propagation on sample with upper void (left) and lower void (right)</td>
<td>15</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Upper void loading force (left) and lower void loading force (right)</td>
<td>16</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Minitab One-Way Anova Case 1</td>
<td>17</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Crack Propagation</td>
<td>18</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Sample with a void of 25 microns (left) and 40 microns (right)</td>
<td>19</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Sample after failure with a void of 25 microns (left) and 40 microns (right)</td>
<td>20</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Crack propagation on sample with 25 microns (left) and 40 microns (right)</td>
<td>20</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Minitab One-Way Anova Case 2</td>
<td>21</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Distance from the lower wall of 20 microns</td>
<td>23</td>
</tr>
<tr>
<td>Figure 6.2</td>
<td>Distance from the lower wall of 40 microns</td>
<td>23</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Distance from the lower wall of 70 microns</td>
<td>24</td>
</tr>
<tr>
<td>Figure 6.4</td>
<td>Distance from the lower wall of 100 microns</td>
<td>24</td>
</tr>
<tr>
<td>Figure 6.5</td>
<td>Distance from the lower wall of 200 microns</td>
<td>24</td>
</tr>
<tr>
<td>Figure 6.6</td>
<td>Crack propagation at different distance from the lower wall: (a) 20 microns (b) 40 microns (c) 70 microns (d) 100 microns (e) 200 microns</td>
<td>25</td>
</tr>
<tr>
<td>Figure 6.7</td>
<td>Loading force vs. distance from the lower wall</td>
<td>26</td>
</tr>
<tr>
<td>Figure 6.8</td>
<td>Loading force vs. distance from the lower wall second run</td>
<td>26</td>
</tr>
<tr>
<td>Figure 6.9</td>
<td>Minitab One-Way Anova Case 3 Y-axis</td>
<td>27</td>
</tr>
<tr>
<td>Figure 6.10</td>
<td>Distance from the center of 875 microns</td>
<td>28</td>
</tr>
<tr>
<td>Figure 6.11</td>
<td>Distance from the center of 437.5 microns</td>
<td>28</td>
</tr>
<tr>
<td>Figure 6.12</td>
<td>Distance from the center of 218.75 microns</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6.13</td>
<td>Sample with void in the center</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6.14</td>
<td>Crack propagation at distance from the center of: (a) 0 microns (b) 875 microns (c) 437.5 microns (d) 218.75 microns (e) 200 microns</td>
<td>29</td>
</tr>
<tr>
<td>Figure 6.15</td>
<td>Loading force vs. distance from center</td>
<td>30</td>
</tr>
<tr>
<td>Figure 6.16</td>
<td>Loading force vs. distance from the center second simulation</td>
<td>31</td>
</tr>
<tr>
<td>Figure 6.17</td>
<td>Minitab One-Way Anova Case 3 X-axis</td>
<td>32</td>
</tr>
<tr>
<td>Figure 7.1</td>
<td>Double void along the y-axis</td>
<td>33</td>
</tr>
<tr>
<td>Figure 7.2</td>
<td>Single void on the center of the sample</td>
<td>34</td>
</tr>
<tr>
<td>Figure 7.3</td>
<td>Crack propagation: (a) Double void along the y-axis (b) single void on the center</td>
<td>34</td>
</tr>
<tr>
<td>Figure 7.4</td>
<td>Minitab One-Way Anova Case 4 Quantity of voids along the Y-axis</td>
<td>35</td>
</tr>
<tr>
<td>Figure 7.5</td>
<td>Double void along the x-axis</td>
<td>37</td>
</tr>
<tr>
<td>Figure 7.6</td>
<td>Single void along the x-axis</td>
<td>37</td>
</tr>
<tr>
<td>Figure 7.7</td>
<td>Crack propagation: (a) Double void along the x-axis (b) single void along the x-axis</td>
<td>37</td>
</tr>
<tr>
<td>Figure 7.8</td>
<td>Minitab One-Way Anova Case 4 Quantity of voids along the X-axis</td>
<td>39</td>
</tr>
<tr>
<td>Figure 8.1</td>
<td>Sample with clusters</td>
<td>40</td>
</tr>
<tr>
<td>Figure 8.2</td>
<td>Sample without clusters</td>
<td>40</td>
</tr>
<tr>
<td>Figure 8.3</td>
<td>Crack propagation: (a) Cluster sample (b) Sample with no clusters</td>
<td>41</td>
</tr>
</tbody>
</table>
Figure 8.4 Minitab One-Way Anova Case 5 Clusters .................................................................42
Figure 9.1 Sample under indentation test: (a) Sample without clusters (b) Sample with clusters ....43
Figure 9.2 Crack propagation: (a) Sample without clusters (b) Sample with clusters .................43
Chapter 1: Introduction

The increasing growth of production and applications in the engineering and biomedical fields of silicon nitride since its discovery has increased the necessity to understand its reliability. In recent years with the constant advance of the technology, improved processing techniques have been developed to reduce the flaws on the ceramic [1]. Fabricating pure dense silicon nitride is difficult since it contains a high degree of covalent bonding between silicon and nitrogen [2].

Ceramics are under development to be produced at large scale with significant improvements to have a tougher, strong and stable material. Bioceramic are separated in two families “bioinert and bioactive” the main difference is bioinert does not create direct bone-material interface unless it is subject to compression to have a successful bone ingrowth. For the next decade ceramics will change from micro to nano-structure to have higher hardness which gives access to new applications. [6]

Applications of silicon nitride are mainly focused on high temperature resistance products such as turbines, bearings, missiles and electronic substrates among others [2]. Researchers are evaluating the performance of the ceramic inside the human body, mainly focus on being an alternative material to replace the alumina on artificial knees-joint, hip-balls and acetabula due to the high thermal resistance, high strength and resistance to oxidation of silicon nitride [3]. Some experimentation has been done to demonstrate the bone growth around the implant and it has proven its high quality with the presence of nutrients [4].

Discrete Element Method was employed for the analysis. This methodology was introduced by Cundall [1] and it is use for the analysis of rock-mechanics and soils. The importance of this experimental procedure is the increasing applications silicon nitride is having in the Biomedical Field where the reliability of the implants or the bearings needs to be maximized. A fracture of these applications depends completely on the microcracks propagation that can lead to failure [5]. During this
experimentation several manufacturing defects such as voids were created and analyze using Discrete Element Method.

In this experimental research a sample of silicon nitride was modeled with the support of the software PFC2D represented as a collection of non-uniform rigid balls with elastic properties interacting among them, capable of fracturing when bonds break. The interaction of particles is treated as a dynamic process with states of equilibrium. Several simulations were performed with strategically placed voids generated at the same time of the sample. For the purpose of this investigation a four point bending test was performed on the sample to calculate the loading force and understand the crack initiation to establish the relationship of the void position with the failure.

1.1 Research Objective

Silicon Nitride is considered as the principal choice of material used for applications requiring lifetime performance. Even though the applications of this ceramic are increasing, it has presented difficulties for the manufacturer to produce a homogeneous microstructure. Pure silicon nitride has been a challenge due to its high degree of covalent bonding. Nowadays new manufacture processes have been developed to improve the fabrication techniques to produce more reliable parts, considering at the same time cost effective solutions.

Heterogeneous Silicon Nitride has the disadvantage of being more susceptible to fatigue and wear causing a pronounced damage. New technologies have been introduce to improve the quality of the ceramics surface by eliminating micro-cracks or any abnormality on the surface that could be present on the ceramic. The difficulty in experimentation leads us to use for this thesis a non-destructive evaluation based on numerical simulations using Discrete Element Method with the support of the software PFC2D

Research has been developed to understand the impact material flaws will have on the crack formation and propagation. After reviewing previous investigations I started questioning the possibility
of applying material flaws on several samples simulated using PFC2D software. Experimental data was used from previous papers to make the comparison with the simulation expecting to have an impact on the reliability of the silicon nitride depending on the flaws.
Chapter 2: Literature Review

2.1 Ceramics Properties

To introduce the topic the first step is to understand the classification of materials according to the material engineering group which separates them in five called metals, polymers, ceramics, semiconductors and composites. Ceramics have this classification due to their association with a mixed bonding having no discrete particles. The most common types are oxides, nitrides and carbides; the difference from ceramics to other materials is their origin ceramics do not come from living organisms. An interesting fact is that the name “ceramics” comes from the activity of burning material to create a product this is the main reason even though the material has changed, the process of manufacturing has remained unchanged. [6]

Since the earth’s crust is compose of materials that build ceramics, ceramics have developed important properties that have made them a choice for some of the main challenges of today’s industry. Some of the advantages of ceramics over other materials are the following:

- Brittleness at room temperature, but not at high temperature
- Valence electrons are tied allowing a higher thermal and electrical conductivity
- Ceramics are stronger in compression than in tension
- Stability on chemical and thermal environments
- Color
- Advance ceramics have improved properties that were developed in the past century

Ceramics are characterized by their properties as: electrical, magnetic, optical, chemical, nuclear, thermal and biological. Also there are two main groups to be considered after the characterization that are traditional and advanced. Advanced Ceramics have improved properties to have more applications to respond to the growing engineering necessities to include new materials to keep up with the technology
advances. In contrast traditional ceramics are high volume products that are used for common applications such as pottery, dinnerware and other similar products. [6]

2.1.1 CERAMICS AREAS OF DEVELOPMENT

- **Structural Ceramics**: to increase the application of these materials the main key factors that need to be improved are reliability, reproducibility and reducing the final cost of the product. Some examples are Silicon Nitride, Silicon Carbide, Zirconia, Boron Carbide and Alumina.[6]

- **Electronic Ceramics**: in the future the improvements will concentrate on integrating the existing semiconductor technology, improving processing and enhancing compatibility with other materials.[6]

- **Bioceramics**: these materials have many concerns as matching the mechanical properties to human tissues, increasing the reliability and improving the processing method.[6]

- **Coating and films**: this application is used for cost saving by applying a coat on the material instead of having the material built entirely of ceramic. This will enhance the properties of the material used, for this reason the researchers are focusing on understanding film deposition and growth.[6]

- **Composites**: the purpose of this is to increase the strength and wear resistance of the material by developing compatible combination of the materials understanding the interfaces.[6]

2.1.2 CERAMICS RELIABILITY

Ceramics have played an important role in the biomedical field, commonly defined as inorganic material suitable for introduction into the living tissue. In 1965 the first ceramic met the reliability needed to be implemented in the biomedical applications; unfortunately it has not been tough and strong enough to create the interface with the bone. There are two main types of ceramics called ‘Bioinert and Bioactive’; the main difference is the capacity to create bone ingrowth when place in-vivo material.
Bioactive materials have the advantage of having similar properties to the mineral part of the bone while bioinert has no direct bone-material interface created and this material is hardly used as bone fillers. Also compare with metals, ceramics have an advantage for dental applications, the color of the material could reach white or ivory. It does not have corrosion problems as metals usually making it become a prefer material for dental restoration even with the disadvantage of the aging issue presented at the oral environment. [7]

The reliability needed for in vivo implants needs to be more than 30 years to be considered a successful alternative for young and active patients. Currently the bone substitution eliminated the risk of any transmission of diseases and it involves a less invasive surgery. Ceramics have a slow crack growth guaranteeing the increase in time of service in-vivo and the fact of having a good hardness with low wear rates. [8] In recent times with the support of the research done on these materials the in vivo failure rate has achieved less than 0.01% [7]

Ceramic materials are brittle; this problem has been approached by increasing the toughness with the implementation of composite materials to produce a homogeneous component with smaller defects increasing the wear resistance. Perhaps it is not suitable to avoid imperfections during the processing of biomedical materials, but with the complete detection, the crack can be analyzed before the occurrence of an in-vivo failure. A subcritical crack growth is a risk due to its sensitivity to extraneous variables that can accelerate the failure as temperature. [8]

2.1.3 Ceramics Evolution

During 1960 the application of ceramics was intended to provide tissue ingrowth and have an inert bioceramic with longevity. The first proposal was the application of aluminum oxide ceramic for dental restoration and orthopedic. Even thought it was successful on dental applications the porosity of the material was inadequate to be stable. Several ceramics were analyzed as polycrystalline alumina and
single crystalline sapphire, unfortunately the brittleness of these materials was a limitation to be considered reliable to resist loading forces. [9]

During the next decade researcher based their efforts analyzing calcium aluminates and several ceramics were introduced as oxide ceramics of aluminum, zirconium, titanium, nitrides among others. Having extended the possibilities of biomaterials increased their application for surgical implant applications. The evolution biomaterials had on 1980 increased the reliability of oxide materials to achieve a stable interface with bone and dental devices. Even though the advance in ceramics was constant there were some major issues that delayed its development as the biodegradation which lead to the application of calcium phosphate that could be reabsorbed within months of implantation. [9]

Currently ceramics are having an increase in the demand for dental restoration as people is more concerned of having a healthy and nice smile. The success of ceramics in this field is the color and the success the restoration has on patients. For the next couple decades researchers will focus on the development of two biomaterials: glass ceramics and sintered ceramics, the main challenge is the highly aesthetic required having the appearance of natural teeth. The manufacture process of these materials needs to be reliable to increase the strength and toughness. [10]

Ceramics is a growing business applied in several fields as the defense industry, engineering, automotive, aerospace even the oil industry and it is considered as one of the prefer materials meeting the requirements of corrosion-resistant, light and strong. Advance ceramics include oxides, nitrides, carbides, borides, silicates, glass ceramics and composite materials being one of the most common silicon nitride applied on high performance applications. Ceramics have developed not only in the medical industry, but also on the automotive to be applied in high temperature components to improve the efficiency and be a cost-effective alternative. Currently due to the low demand of some ceramic materials and the machining process cost it may not be a good alternative, but a reduction on the price could be obtained with high production. [11]
Chapter 3: Experimental Procedure

3.1 PFC2D Software

A flow model is created to simulate the mechanical behavior of a “collection of particles that occupied a finite amount of space”. In this model the particles displace independently interacting only on contacts between particles. Another alternative is to model allowing the particles to be bonded on the contact points creating tensile forces between particles. The assumptions considered are the following:

![Figure 3.1 Particle Properties](image)

3.1.1. Parallel Bond Model

This type of bond describes the behavior of cementation material between two balls. Compare with contact, parallel bonds are able to transmit both forces and moments.

3.1.2. Discrete Element Method

PFC2D software helps us model the movement and interaction of rigid balls using DEM. The dynamic behavior of the particles is represented numerically by a timestepping algorithm, this being so small that disturbances are difficult to propagate among particles. Any force acting upon the particle is completely developed by the interaction with the particles which it is in contact [12].
3.1.3 Important concepts

- **Newton’s Second Law:** is used to understand the motion each particle has in result of the forces applied to it. This law could be simply summarized with the following statement the acceleration of the object depends on the force applied and the mass of the object. If the force is increased the acceleration increases.

- **Cycle:** is a timestepping algorithm that updates the velocity and position based on the resultant force and moment on the particle.

3.2 Modeling the Sample

The creation of the silicon nitride sample was done with the support of PFC2D based on four basic steps: (1) Generating a compact initial sample, (2) Installing specified isotropic stress, (3) Eliminating Floaters and (4) Finalizing sample generation [12]. To accomplish a successful simulation the microparameters, Table 1, are considered the properties of the particles generated. The dimensions of the specimen generated for this simulation were 3.5 mm in length and 1.25 mm in width. The number of particles generated is 20,796 particles.

![Sample Generation](image)

**Figure 3.2** Sample Generation
The complexity of the software allows the user to simulate particles with different size and randomly distributed. The specimens are closer to brittle materials with variations in the microstructural properties. In order to simulate the silicon nitride for the thesis, parameters were selected related to the Young’s modulus and Poisson’s ratio as seen on table 3.1.

Parameters shown on table 3.1 were selected from a paper developed at Kansas State University. PFC2D properties are based in particle level for this reason a numerical biaxial test was conducted to investigate the macroproperties in order to extract the young’s modulus of elasticity, poisson ratio and the compressive strength. After determining the macroproperties, the theoretical relationship with the microproperties was determined to generate a silicon nitride sample. [8]

**Table 3.1** Microparameters of Silicon Nitride Ceramics [12]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Particle Density (kg/m³)</td>
<td>3200</td>
</tr>
<tr>
<td>Particle Contact Modulus (GPa)</td>
<td>220</td>
</tr>
<tr>
<td>Particle Stiffness Ratio</td>
<td>1.275</td>
</tr>
<tr>
<td>Particle Friction Coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>Parallel Bond Radius Multiplier</td>
<td>1</td>
</tr>
<tr>
<td>Parallel Bond Modulus (Gpa)</td>
<td>220</td>
</tr>
<tr>
<td>Parallel Bond Stiffness Ratio</td>
<td>1.275</td>
</tr>
<tr>
<td>Parallel Bond Normal Strength Mean (MPa)</td>
<td>1600</td>
</tr>
<tr>
<td>Parallel Bond Normal Strength Std Dev (MPa)</td>
<td>400</td>
</tr>
<tr>
<td>Parallel Bond Shear Strength Mean (MPa)</td>
<td>3200</td>
</tr>
<tr>
<td>Parallel Bond Shear Strength Std Dev (MPa)</td>
<td>800</td>
</tr>
</tbody>
</table>

After the sample is done a four point bending test was generated to simulate the inelastic deformation of the specimen and bond strength in order to analyze the propagation of microcracks. Four balls with a radius of 0.225 mm were loaded on the sample; the fixed supporting balls are
separated 1.000 mm from the center of the specimen contrary to the upper which are just 0.500 mm from the center. On the PFC2D code developed, a wall was generated on top of the upper balls with a velocity of 2 m/s applying force to the upper loading balls while the supporting balls are fixed. Under these conditions the four point testing is performed and the crack initiates as the force of the loading balls begins the inelastic deformation.

In figure 3.3 a four point bending test is illustrated, on PFC2D software the force is applied using a wall with an applied velocity to do the testing. As the bending test is being performed the sample starts experiencing a compression and a tension in the sides of the sample.

![Figure 3.3 Four Point Bending Test](image)

**3.3 Cases Selection**

To begin the experimental phase of the thesis several scenarios are considered to understand the crack propagation and the effect it has on the sample’s reliability.
a) Case 1: Upper vs. Lower Wall
b) Case 2: Void Size
c) Case 3: Location
d) Case 4: Voids Quantity
e) Case 5: Clusters Four Point Bending
f) Case 6: Clusters Indentation

All the cases selected have the same microproperties and macroproperties, the unique difference is the addition of flaws on the first four cases. On the last two cases clusters were added to improve the toughness of the sample containing β grains.
Chapter 4: Case 1. Upper vs. Lower Void

4.1 Sample Generation

A specimen of silicon nitride of dimensions 3.5 mm length and 1.25 of height was generated with the microparameters in table 3.1. On two different samples one void of 40 microns was created on the upper and lower wall of the specimens. On the samples the separation from the wall is of approximately 20 microns as shown in figure 4.1.

![Void position on the lower and upper surface](image)

Figure 4.1 Void position on the lower and upper surface

To start the simulation of case 1 a unique void is placed close to the upper wall, after the material flaw is added the crack procedure initiates by removing the walls and applying a loading force directly on the loading balls to start the testing. On the second step of the comparison a new sample is generated and one void is added closer to the lower wall and a four point bending test is started. Prior to start the cycling the samples are created by the software without any crack only having the void as shown in figure 4.2.
During the four point bending test the first cracks developed on the sample are shown on figure 4.3. On the first case with the void close to the upper surface the initial crack was developed in a different position from the void occurring on the left size of the sample. Contrary to the upper void, the lower void started on the void its propagation.

At failure the crack propagation of both simulations were completely different as shown in figure 4.4 and 4.5. According to the figures both samples have a different initiation and the crack has a strong effect on the lower surface of the silicon nitride.
4.2 **RESULTS**

The graphs of figure 4.6 are called “Step vs Load”, their main purpose it to monitor the loading force applied to the silicon nitride sample during the four point bending test. At failure the maximum loading force was applied to the silicon nitride. In table 4.1 the information of the testing performed is recorded, the loading force of the void placed on the upper wall is higher than the one on the lower wall having a difference of 2.504e5 N.

**Table 4.1** Top vs. Bottom Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>0</td>
<td>0.000565</td>
<td>1.725e5</td>
<td>5.921e5</td>
</tr>
<tr>
<td>Bottom</td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.417e5</td>
</tr>
</tbody>
</table>
Table 4.2 Top vs. Bottom Comparison Second Run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>0</td>
<td>0.000565</td>
<td>1.6375</td>
<td>6.233e5</td>
</tr>
<tr>
<td>Bottom</td>
<td>0</td>
<td>-0.000565</td>
<td>1.475e5</td>
<td>3.419e5</td>
</tr>
</tbody>
</table>

Figure 4.6 Upper void loading force (left) and lower void loading force (right)

4.3 Statistical Analysis Case 1

After the two simulations were run on each case, ANOVA was selected as our tool to determine if the position of the void based on these two parameters has a significant effect on the loading force.

- **Hypothesis**

  Ho: There is no indication the position of the void placed on the lower or upper surface affects the loading force

  Ha: There is indication the position of the void placed on the lower or upper surface affects the loading force

- **Decision**

  If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.003 is less than 0.05 we reject Ho at a significance level of 5%.
• Analysis

Figure 4.7 show minitab output after the data was analyzed using One-way ANOVA.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-Loc</td>
<td>1</td>
<td>70702810000</td>
<td>70702810000</td>
<td>290.52</td>
<td>0.003</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>486740000</td>
<td>243370000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>71189550000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 15600  R-Sq = 99.32%  R-Sq(adj) = 98.97%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.000565</td>
<td>2</td>
<td>341800</td>
<td>141</td>
</tr>
<tr>
<td>0.000565</td>
<td>2</td>
<td>607700</td>
<td>22062</td>
</tr>
</tbody>
</table>

Pooled StDev = 15600

Figure 4.7 Minitab One-Way Anova Case 1

4.4 DISCUSSION CASE 1

The origin of the fracture of the silicon nitride sample with a void close to the upper wall was not on the flaw. The sample after the crack procedure shows evidence the propagation followed several directions since the first crack developed was on the left side not in the upper void. In contrast, the sample with the lower void shows evidence that the crack propagation started from the void and ended in the upper surface. The explanation of this phenomenon is shown on figure 4.8 where the force being applied to the silicon nitride which is causing a compression on the sample originating a tension in the opposite direction causing a fracture starting on the lower surface, breaking the sample in two.

According to the minitab analysis of figure 4.7, since the p-value is less than 0.05 the analysis concludes there is indication the position of the void on the lower or upper surface has a significant effect on the loading force at a significance level of 5%. A void in the lower surface may reduce the reliability of the silicon nitride compare with one in the upper region.
Figure 4.8 Crack Propagation
Chapter 5: Case 2. Voids Size

5.1 Sample Generation

For the second case new samples were generated of 1.25 mm height and 3.5 mm width with the parameters specified on table 3.1. The approach for this analysis is the impact the size of the material flaw has on the failure of the silicon nitride since it is critical for having a direct impact on the strength properties of the material. For this case, two simulations were performed having a size difference of 15 microns. The first simulation was done with a void of 25 microns located on the lower surface and on the second the flaw had a radius of 40 microns. The four point bending test started until failure after the void was placed on each sample.

The samples generated are shown in figure 5.1 where the void size has been reduce to understand the effect it will have on the loading force. After the four point bending test is performed the crack propagation is shown on the samples from figure 5.2. The crack propagation could be easily understood by analyzing figure 5.3 where both samples follow a straight crack.

Figure 5.1 Sample with a void of 25 microns (left) and 40 microns (right)
5.2 RESULTS

The size of the void has a negative impact on the strength properties of the silicon nitride. Based on the comparison a smaller void increases the loading force applied to the sample. Two simulations were run and the data was recorded on Table 5.1 and 5.2.

Table 5.1 Size comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 microns void</td>
<td>0</td>
<td>-0.000550</td>
<td>1.7875e5</td>
<td>5.796e5</td>
</tr>
<tr>
<td>40 microns void</td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.417e5</td>
</tr>
</tbody>
</table>

Table 5.2 Size comparison Second Run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 microns void</td>
<td>0</td>
<td>-0.000550</td>
<td>1.550e5</td>
<td>4.739e5</td>
</tr>
<tr>
<td>40 microns void</td>
<td>0</td>
<td>-0.000565</td>
<td>1.475e5</td>
<td>3.419e5</td>
</tr>
</tbody>
</table>
5.3 **Statistical Analysis Case 2**

After two simulations were run on each case, ANOVA was selected as our tool to determine if the size of the void with the values selected has a significant effect on the loading force.

- **Hypothesis**
  
  Ho: There is no indication the size of the void selected has a significant effect on the loading force  
  Ha: There is indication the size of the void selected has a significant effect on the loading force  

- **Decision**
  
  If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.073 is greater than 0.05, then we fail to reject Ho at a significance level of 5%.

- **Analysis**
  
  Figure 5.4 show minitab output after the data was analyzed using One-way ANOVA.

```
<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>1</td>
<td>34206502500</td>
<td>34206502500</td>
<td>12.25</td>
<td>0.073</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>5586265000</td>
<td>2793132500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>39792767500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 52850  R-Sq = 85.96%  R-Sq(adj) = 78.94%

**Individual 95% CIs For Mean Based on Pooled StDev**

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Microns</td>
<td>2</td>
<td>526750</td>
<td>74741</td>
</tr>
<tr>
<td>40 Microns</td>
<td>2</td>
<td>341800</td>
<td>141</td>
</tr>
</tbody>
</table>

Pooled StDev = 52850
```

**Figure 5.4 Minitab One-Way Anova Case 2**

5.4 **Discussion Case 2**

The results obtained in the simulation of a four point bending test done on two silicon nitride samples with voids of different size, show a relationship between the void dimension and the maximum
loading force before fracture. A bigger void causes a reduction on the strength of the ceramics due to the brittleness of the material. The reliability of the material decreases in accordance to the experimental research developed with laser scattering where the fracture origin has a greater intensity if the flaw is larger and closer to the surface which makes the sample weaker. [13]

In contrast the ANOVA shows that at a significance level of 5% there is no indication the radius selected has a significant effect on the loading force.
Chapter 6: Case 3. Location

6.1 Sample Generation: Y-axis

In this case a new silicon nitride sample was simulated with dimensions 1.25 mm width and 3.5 mm length. The material flaws were generated with a radius of 40 microns placed in different locations of the sample. The first approach is to generate a void along the y-axis starting with a distance from the lower wall of 20 microns. The following figures 6.1 through 6.5 show different positions of the voids along the y-axis to understand the effect the distance from the lower surface has on the loading force.

Figure 6.1 Distance from the lower wall of 20 microns

Figure 6.2 Distance from the lower wall of 40 microns
As shown in figure 6.6 the crack evolution during the change of depth from the lower wall to the center of the silicon nitride is interesting, the voids closer to the lower wall a straight fracture is formed, but as the void starts getting closer to the center the crack propagation starts deviating to the sides of the sample to finally at 200 microns crack is not on the void. On the first case a void is simulated closer to the upper void on it we are able to visualize that the crack has a “Y-shape”.
Figure 6.6 Crack propagation at different distance from the lower wall: (a) 20 microns (b) 40 microns (c) 70 microns (d) 100 microns (e) 200 microns

6.2 RESULTS: Y-AXIS

There is a significant relationship between the position of the void along the y-axis and the loading force as shown on figure 6.7 and 6.8 having a difference in the loading force of $2.497e5$ Newton as the void is closer to the center of the sample.

Table 6.1 Depth Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Microns</td>
<td>0</td>
<td>-0.000385</td>
<td>1.712e5</td>
<td>5.914e5</td>
</tr>
<tr>
<td>100 Microns</td>
<td>0</td>
<td>-0.000485</td>
<td>1.712e5</td>
<td>5.845e5</td>
</tr>
<tr>
<td>70 Microns</td>
<td>0</td>
<td>-0.000515</td>
<td>1.6375e5</td>
<td>4.61e5</td>
</tr>
<tr>
<td>40 Microns</td>
<td>0</td>
<td>-0.000545</td>
<td>1.625e5</td>
<td>4.64e5</td>
</tr>
<tr>
<td>20 Microns</td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.417e5</td>
</tr>
</tbody>
</table>
Figure 6.7 Loading force vs. distance from the lower wall

Table 6.2 Depth Comparison Second Run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Microns</td>
<td>0</td>
<td>-0.000385</td>
<td>1.650e5</td>
<td>6.212e5</td>
</tr>
<tr>
<td>100 Microns</td>
<td>0</td>
<td>-0.000485</td>
<td>1.550e5</td>
<td>4.603e5</td>
</tr>
<tr>
<td>70 Microns</td>
<td>0</td>
<td>-0.000515</td>
<td>1.558e5</td>
<td>4.693e5</td>
</tr>
<tr>
<td>40 Microns</td>
<td>0</td>
<td>-0.000545</td>
<td>1.500e5</td>
<td>3.907e5</td>
</tr>
<tr>
<td>20 Microns</td>
<td>0</td>
<td>-0.000565</td>
<td>1.475e5</td>
<td>3.419e5</td>
</tr>
</tbody>
</table>

Figure 6.8 Loading force vs. distance from the lower wall second run

6.3 Statistical Analysis Case 3 Y-axis

- Hypothesis
Ho: There is no indication the position of the void on the y-axis has a significant effect on the loading force

Ha: There is indication the position of the void on the y-axis has a significant effect on the loading force

- **Decision**
  
  If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.016 is less than 0.05 then we reject Ho at a significance level of 5%.

- **Analysis**
  
  Figure 6.9 show minitab output after the data was analyzed using One-way ANOVA.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C11</td>
<td>4</td>
<td>79134870000</td>
<td>19783717500</td>
<td>9.09</td>
<td>0.016</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>10877750000</td>
<td>2175550000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>90012620000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 46643 R-Sq = 87.92% R-Sq(adj) = 78.25%

### One-way ANOVA: LF Y Axis versus C11

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 microns</td>
<td>2</td>
<td>522400</td>
<td>87823</td>
</tr>
<tr>
<td>200 microns</td>
<td>2</td>
<td>606300</td>
<td>21072</td>
</tr>
<tr>
<td>40 microns</td>
<td>2</td>
<td>427350</td>
<td>51831</td>
</tr>
<tr>
<td>70 microns</td>
<td>2</td>
<td>465150</td>
<td>5869</td>
</tr>
<tr>
<td>Lower</td>
<td>2</td>
<td>341800</td>
<td>141</td>
</tr>
</tbody>
</table>

Pooled StDev = 46643

**Figure 6.9** Minitab One-Way Anova Case 3 Y-axis

### 6.4 Discussion Case 3 Y-axis

For the y-axis comparison the graph follows a positive direction as the void is closer to the center of the sample increasing the loading force applied before fracture. There is a strong relationship between the depth position and the reliability of the sample. The reliability of the silicon nitride increases as the void is closer to the center of the sample. If there is a significant distance separating the void from the lower wall it will create a “material barrier” which will delayed the propagation. At a significance level
of 5% there is indication the position of the void along the y-axis has a significant effect on the loading force.

**6.5 Sample Generation: X-axis**

On the second part of the case a sample was generated with voids along the x-axis on the inner region of the four point bending test. The inner region of the four point bending test starts on the positive x-axis from 0.000100 to 0.00145. As shown in figures 6.10 through 6.13 different scenarios were run to determine the effect it will represent to the loading, also the crack propagation is recorded in figure 6.14, even though the direction of the failure is different among the simulations the origin is the void.

![Figure 6.10 Distance from the center of 875 microns](image1)

**Figure 6.10** Distance from the center of 875 microns

![Figure 6.11 Distance from the center of 437.5 microns](image2)

**Figure 6.11** Distance from the center of 437.5 microns
Figure 6.12 Distance from the center of 218.75 microns

Figure 6.13 Sample with void in the center

Figure 6.14 Crack propagation at distance from the center of: (a) 0 microns (b) 875 microns (c) 437.5 microns (d) 218.75 microns
6.6 RESULTS: X-AXIS

Even though there is an effect on the loading force with the change of position along the x-axis the trend is not constant, for this reason a second simulation was performed to record new data to have a statistical comparison. Figures 6.13 and 6.14 show the effect an increase on the distance on the x-axis has on the loading force.

Table 6.3 X-axis comparison first run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right #1</td>
<td>0.0008750</td>
<td>-0.000565</td>
<td>1.634e5</td>
<td>4.493e5</td>
</tr>
<tr>
<td>Right #2</td>
<td>0.0004375</td>
<td>-0.000565</td>
<td>1.575e5</td>
<td>3.358e5</td>
</tr>
<tr>
<td>Right #3</td>
<td>0.00021875</td>
<td>-0.000565</td>
<td>1.575e5</td>
<td>3.962e5</td>
</tr>
<tr>
<td>Center Void</td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.417e5</td>
</tr>
</tbody>
</table>

Table 6.4 X-axis comparison second run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right #1</td>
<td>0.0008750</td>
<td>-0.000565</td>
<td>1.650e5</td>
<td>6.043e5</td>
</tr>
<tr>
<td>Right #2</td>
<td>0.0004375</td>
<td>-0.000565</td>
<td>1.550e5</td>
<td>4.435e5</td>
</tr>
<tr>
<td>Right #3</td>
<td>0.00021875</td>
<td>-0.000565</td>
<td>1.575e5</td>
<td>4.658e5</td>
</tr>
<tr>
<td>Center Void</td>
<td>0</td>
<td>-0.000565</td>
<td>1.475e5</td>
<td>3.419e5</td>
</tr>
</tbody>
</table>

Figure 6.15 Loading force vs. distance from center
6.7 Statistical Analysis Case 3 X-Axis

- **Hypothesis**

  Ho: There is no indication the position of the void on the y-axis has a significant effect on the loading force

  Ha: There is indication the position of the void on the y-axis has a significant effect on the loading force

- **Decision**

  If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.232 is greater than 0.05 then we fail to reject Ho at a significance level of 5%.

- **Analysis**

  Figure 6.15 show minitab output after the data was analyzed using One-way ANOVA.
### One-way ANOVA: LF X Axis versus C19

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C19</td>
<td>3</td>
<td>49995656838</td>
<td>16665218946</td>
<td>2.18</td>
<td>0.232</td>
</tr>
<tr>
<td>Error</td>
<td>4</td>
<td>30509683450</td>
<td>7627420863</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>80505340288</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ S = 87335 \quad \text{R-Sq} = 62.10\% \quad \text{R-Sq(adj)} = 33.68\% \]

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>2</td>
<td>341800</td>
<td>141</td>
</tr>
<tr>
<td>Right #1</td>
<td>2</td>
<td>554865</td>
<td>149291</td>
</tr>
<tr>
<td>Right #2</td>
<td>2</td>
<td>389650</td>
<td>76155</td>
</tr>
<tr>
<td>Right #3</td>
<td>2</td>
<td>431000</td>
<td>49215</td>
</tr>
</tbody>
</table>

---

**Figure 6.17** Minitab One-Way Anova Case 3 X-axis

#### 6.8 Discussion Case 3 X-axis

At a significance level of 5% the analysis shows there is no significant effect on the position of the void in the x-axis. The crack propagation starts on the void and starts tilting to the center in direction to the upper surface.
Chapter 7: Case 4. Voids Quantity

7.1 Sample Generation: Voids Along the Y-axis

The number of flaws on the Silicon Nitride could be eliminated or reduce by refinements on processing and finishing. Having fewer flaws in the material allows the manufacturer to have a product with higher reliability and with a strength that could last for a lifetime. Having considered the importance of a homogeneous material for this case, a simulation was done based on the possibility of having more than one void in the material to understand how the reliability of the material is affected. The quantity of voids after the manufacturing process of the silicon nitride is unpredictable in this case the analysis was done having an additional void simulated on the silicon nitride sample. In the first approach two voids were placed close enough to have a barrier of balls between them with a radius of 40 microns and a separation of approximately 85 microns as shown in figure 7.1. The comparison is made with a single void of 40 microns as shown in figure 7.2.

Figure 7.1 Double void along the y-axis
**Figure 7.2** Single void on the center of the sample

Figure 7.3 shows the crack propagation of having more than one void along the y-axis where the path the crack follows is toward the upper surface of the silicon nitride.

(a)                (b)

**Figure 7.3** Crack propagation: (a) Double void along the y-axis (b) single void on the center

### 7.2 RESULTS: DOUBLE VOID ALONG THE Y-AXIS

An increase in the quantity of voids along the y-axis has a significant impact on the loading force affecting the strength of the materials developing a fracture at an inferior force.

### Table 7.1 Single vs. double void along the y-axis comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>0</td>
<td>-0.000400</td>
<td>1.525e5</td>
<td>2.707e5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.417e5</td>
</tr>
<tr>
<td>Single</td>
<td>0</td>
<td>-0.000565</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.2 Single vs. double void along the y-axis comparison second run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>0</td>
<td>-0.000400</td>
<td>1.4915e5</td>
<td>3.474e5</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>-0.000565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>0</td>
<td>-0.000565</td>
<td>1.600e5</td>
<td>3.419e5</td>
</tr>
</tbody>
</table>

7.3 **Statistical Analysis Case 4 Y-axis**

- **Hypothesis**

Ho: There is no indication the quantity of voids in the y-axis have a significant effect on the loading force.

Ha: There is indication the quantity of voids in the y-axis have a significant effect on the loading force.

- **Decision**

If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.483 is greater than 0.05 then we fail to reject Ho at a significance level of 5%.

- **Analysis**

Figure 7.4 show minitab output after the data was analyzed using One-way ANOVA.

**One-way ANOVA: LF Qy versus QY axis**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>QY axis</td>
<td>1</td>
<td>1072562500</td>
<td>1072562500</td>
<td>0.73</td>
<td>0.483</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>2941465000</td>
<td>1470732500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>4014027500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 38350  R-Sq = 26.72%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>2</td>
<td>309050</td>
<td>54235</td>
</tr>
<tr>
<td>Single</td>
<td>2</td>
<td>341800</td>
<td>141</td>
</tr>
</tbody>
</table>

---

Pooled StDev = 38350

**Figure 7.4 Minitab One-Way Anova Case 4 Quantity of voids along the Y-axis**
7.4 Discussion Case 4 Double Void Y-axis

At a significance level of 5% we may conclude the number of voids along the y-axis does not have a significant effect on the loading force. Even though based on the loading force obtained we may infer there was a negative effect on the loading force due to the position and quantity of voids along the center of the y-axis compare with a sample of silicon nitride with one void close to the lower surface. I assume there is a small effect on having two voids with a small separation which decreases the strength of the material since it has the effect of a flaw with a bigger radius. The quantity of voids weakens the silicon nitride in accordance to the research done with experimental data and the application of laser scattering where low fracture strength is developed due to a group of material flaws along the fracture line. [13]

7.5 Sample Generation: Voids along the X-axis

Having considered the importance of a homogeneous silicon nitride a new simulation was done to analyze the effect a different quantity of voids and size has on the loading force. On this simulation two voids the first with a radius of 40 microns and the second of 25 microns was added along the x-axis as shown in figures 7.5 and 7.6 having a distance from the voids is of 700 microns. After the simulation was performed a comparison was made with a single void of 40 microns. The purpose of the generation of voids with different sizes was to understand the origin of the crack propagation.
Figure 7.5 Double void along the x-axis

Figure 7.6 Single void along the x-axis

In figure 7.6 the crack propagation starts from the void with the bigger radius toward the center of the sample.

Figure 7.7 Crack propagation: (a) Double void along the x-axis (b) single void along the x-axis
7.6 **RESULTS: DOUBLE VOID ALONG THE X-AXIS**

The double void along the x-axis with different size does not have a significant impact on the loading force of the material. A second simulation was run to complete the proper comparison of the case.

**Table 7.3** Single vs. double void along the x-axis comparison first run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>0.00035</td>
<td>-0.000565</td>
<td>1.575e5</td>
<td>3.873e5</td>
</tr>
<tr>
<td></td>
<td>-0.00035</td>
<td>-0.000565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>-0.00035</td>
<td>-0.000565</td>
<td>1.5125e5</td>
<td>3.713e5</td>
</tr>
</tbody>
</table>

**Table 7.4** Single vs. double void along the x-axis comparison second run

<table>
<thead>
<tr>
<th>Model</th>
<th>X</th>
<th>Y</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>0.00035</td>
<td>-0.000565</td>
<td>1.550e5</td>
<td>4.593e5</td>
</tr>
<tr>
<td></td>
<td>-0.00035</td>
<td>-0.000565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>-0.00035</td>
<td>-0.000565</td>
<td>1.5625e5</td>
<td>4.608e5</td>
</tr>
</tbody>
</table>

7.7 **STATISTICAL ANALYSIS CASE 4 X-AXIS**

- **Hypothesis**

Ho: There is no indication the quantity of voids in the x-axis with different size have a significant effect on the loading force

Ha: There is indication the quantity of voids in the x-axis with different size have a significant effect on the loading force

- **Decision**

If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.911 is greater than 0.05 then we fail to reject Ho at a significance level of 5%.

- **Analysis**

Figure 7.8 show minitab output after the data was analyzed using One-way ANOVA.
### One-way ANOVA: LF B&S versus QB&S

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB&amp;S</td>
<td>1</td>
<td>52562500</td>
<td>52562500</td>
<td>0.02</td>
<td>0.911</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>659712500</td>
<td>3298562500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>664968750</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 57433   R-Sq = 0.79%   R-Sq(adj) = 0.00%

#### Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double</td>
<td>2</td>
<td>423300</td>
<td>50912</td>
</tr>
<tr>
<td>Single</td>
<td>2</td>
<td>416050</td>
<td>63286</td>
</tr>
</tbody>
</table>

Pooled StDev = 57433

---

**Figure 7.8** Minitab One-Way Anova Case 4 Quantity of voids along the X-axis

### 7.8 Discussion Case 4 Double Void X-axis

At a significance level of 5% we may conclude the quantity of voids of different size along the x-axis does not have a significant effect on the loading force. On this case the simulation was done with two voids with different size with a separation of 700 microns along the x-axis, the crack propagation started on the bigger void in accordance to the research developed with experimental tests using laser scattering where the propagation started on the bigger flaw. [13]
Chapter 8: Case 5. Clusters Four Point Bending

8.1 Sample Generation

Clusters have an impact on the strength of the silicon nitride simulation. The importance of having a coarse sample to get a closer approximation to real grains of the silicon nitride was simulated by grouping randomly a maximum of 10 balls per cluster. The macroproperties and microproperties remained as in table 3.1. The comparison was made with a sample with no flaws shown in figure 8.2 and both samples were tested on a four point bending until failure. Clusters were simulated with bond strength of 1e30 Pa to avoid any breakage within the cluster. Clusters have the ability to form irregular grains that cannot rotate easily causing an increase in the load force and reducing the crack propagation. A cluster sample is shown in figure 8.1 before and after the crack initiation.

![Figure 8.1 Sample with clusters](image1)

![Figure 8.2 Sample without clusters](image2)
After the four point bending test the crack propagation was recorded on figure 8.3 to make the comparison of the path the crack followed during the testing.

![Crack propagation images](image)

**Figure 8.3** Crack propagation: (a) Cluster sample (b) Sample with no clusters

### 8.2 Results

Silicon Nitride samples with clusters have a positive effect on the loading force compared with single balls having a significance force difference of \(2.546 \times 10^5\) N.

<table>
<thead>
<tr>
<th>Model</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>1.825e5</td>
<td>8.193e5</td>
</tr>
<tr>
<td>No voids</td>
<td>1.725e5</td>
<td>5.646e5</td>
</tr>
</tbody>
</table>

**Table 8.1** Cluster vs. single balls comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>Step</th>
<th>Loading Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>1.725e5</td>
<td>7.715e5</td>
</tr>
<tr>
<td>No voids</td>
<td>1.650e5</td>
<td>6.383e5</td>
</tr>
</tbody>
</table>

**Table 8.2** Cluster vs. single balls comparison second run

### 8.3 Statistical Analysis Case 5 Clusters

- **Hypothesis**

  Ho: There is no indication clusters have a significant effect on the loading force

  Ha: There is indication clusters have a significant effect on the loading force
• Decision

If p value is greater than alpha accept Ho if not reject it. P value for the comparison is 0.048 is less than 0.05 then we reject Ho at a significance level of 5%.

• Analysis

Figure 8.4 show minitab output after the data was analyzed using One-way ANOVA.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNV</td>
<td>1</td>
<td>37616602500</td>
<td>37616602500</td>
<td>19.50</td>
<td>0.048</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>3858265000</td>
<td>1929132500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>41474867500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 43922 R-Sq = 90.70% R-Sq(adj) = 86.05%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>2</td>
<td>795400</td>
<td>33800</td>
</tr>
<tr>
<td>No voids</td>
<td>2</td>
<td>601450</td>
<td>52114</td>
</tr>
</tbody>
</table>

Pooled StDev = 43922

**Figure 8.4** Minitab One-Way Anova Case 5 Clusters

**8.4 Discussion Case 5 Clusters**

At a significance level of 5% we may conclude clusters have a significant effect on the loading force. The addition of clusters to the silicon nitride sample improved the strength of the material and resemble of the real grain structure. In comparison with the four point bending test of the sample generated with no clusters the loading force difference was significant. The clusters bonds were designed to be unbreakable affecting positively the strength of the silicon nitride to have a better resistance to failure. Easy rotation was eliminated with the addition of clusters and a notorious improvement to approximation to the behavior of the material. The results obtained are in accordance to the hypothesis presented on research done previously with the creation of clusters on the sample. [10]
Chapter 9: Case 6. Clusters Indentation

9.1 Sample Generation

A sample generated based on the parameters of table 3.1 with clusters and one without is subject to an indentation test to understand the crack formation around the indenter. Indentation allows the user to understand the hardness of the material under test. It is expected the sample closer to the real Silicon Nitride will generate a specific pattern completely different from the sample with no clusters seen on previous chapters. The testing will be performed placing a loading ball with a radius of 225 microns and one wall above that will start moving at a velocity of 2 m/s on the negative y-axis direction.

Figure 9.1 Sample under indentation test: (a) Sample without clusters (b) Sample with clusters

9.2 Results

At this case the pattern the crack forms on the Silicon Nitride is under analysis, on the figure 9.2 the crack propagation is shown

Figure 9.2 Crack propagation: (a) Sample without clusters (b) Sample with clusters
9.3 Discussion Case 6 Indentation with Clusters

The indentation testing done to a sample with clusters compare with the single balls demonstrated the increase in the strength of the material. The crack figure of the silicon nitride is in accordance to the simulation performed for material removal of brittle ceramics where the initiation of the cracks are close to the cutting tools developing cracks downward and some microcracks away from the cutting tool. Even though the strength is different from both samples the crack propagation has the same origin. [14]
Chapter 10. Conclusions and contributions

The simulations performed with the support of the PFC2D software were in accordance with the experimental results obtained by several researchers in the field. The application of this software as a non-destructive evaluation alternative has proven to simulate brittle ceramics in accordance to their properties and has shown the negative effect material flaws have on the silicon nitride. A reduction in the ceramic’s reliability is mainly produced by random factors that varied based on the position and quantity of voids.

The results have demonstrated the importance the improvement of technologies for the manufacturing of silicon nitride has to produce material with better accuracy and with greater homogeneity. Also this research indicated that subsurface defects have a greater impact on the reliability compared with defects in the center of the sample. Since the applications of silicon nitride are growing on the medical industry having a heterogeneous material with a doubtful reliability makes this ceramic not the first choice for doctors who are making surgical procedures to patients. Patients are looking for solutions to their problems, for this reason the implants are expected to have a lifetime durability to avoid a new surgery.

The contribution this research has is to understand the crack propagation and its origin to be able to determine the reliability of silicon nitride. Even though silicon nitride has proven to be a capable material to withstand high temperatures and loading forces it still have weakness that researchers needs to continue evaluating to make it the best choice.
Chapter 11. Future Research

There is no limit for investigation, ceramics have been studied for more than 40 years and its applications started since our ancestors without being documented. Ceramics have a promising future on all the industry, mainly on the medical industry which makes it an interesting topic to do research in different scenarios. After the literature review and the research done on this thesis there are many questions that still do not have answer. PFC2D is a powerful simulator which could generate a sample that matches at least three different types of silicon nitride: coarse, medium and fine. The particle size used on the thesis simulated more a coarse material which gives completely different results from a silicon nitride with a fine composition. Also adding clusters to the sample changes completely the results of the flaws and the crack propagation.

The thesis developed is just a starting point of the wide variety of flaws a silicon nitride may have after the manufacture process. Experimental and simulation data needs to be increased to do a better analysis; unfortunately limitations are part of research and on this case time determined the scope.
References


Appendix

Bottom Void Code

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ2'
title 'Four Point Bending Test Case 1-B Top Vs Bottom'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.000565 radius 0.40e-4
delete ball range group Tunnel
crk_init

delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand

command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;------------------------------------------------------------------------------------------------------------------------
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
   vel_w = vel_w + dv_w
   fvel_w = vel_w
   command
      wall id=10 yvel= @vel_w
      cycle @niter_w
   end_command
end_loop
end
;====================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end
;====================================================================
loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004
set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection
hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz2.SAV;
return;
;EOF: b4p.DVR
new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call ftt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ1'
title 'Four Point Bending Test Case 1-A Top Vs Bottom'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5

;  
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;

set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 0.000565 radius 0.40e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; ===================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT: vel_w    - final platen velocity    (float)
;        cyc_w    - total number of cycles   (integer)
;        stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
   vel_w = vel_w + dv_w
;   fvel_w = vel_w
command
   wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end

; ===================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz1.SAV
;
return
;===============================================================================================
:=

;EOF: b4p.DVR
new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ21'
title 'Four Point Bending Test Case 2- Size'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.00055 radius 0.25e-4
delete ball range group Tunnel

crk_init

delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end
;

-----------------------------
def acc_wall
;
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [vel_w] over approximately [niter_w] cycles
;       in [stages_w] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1, stages_w)
   vel_w = vel_w + dv_w
;  fvel_w = vel_w
command
   wall id=10  yvel= @vel_w
cycle @niter_w
end_command
end_loop
end
;

-----------------------------
def deflection
wid=10
wp=find_wall(wid)
deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400  stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz21.SAV
;
return
;=====================================================================
;EOF: b4p.DVR
LOCATION Y-AXIS 40 MICRONS

new
set safe_conversion on
set random=1200
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ21'
title 'Four Point Bending Test Case 2- Size'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
; SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;

set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.00055 radius 0.25e-4
delete ball range group Tunnel
crk_init

delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
;  fvel_w = vel_w
command
    wall id=10  yvel= @vel_w
cycle @niter_w
end_command
end_loop
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz21.SAV
;
return
;==============================================================================================
new
set safe_conversion on
set random=1200
set disk on
set echo on
set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ21'
title 'Four Point Bending Test Case 2- Size'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5;

SET md_wEcfac=5.0
SET tm_req_isost=-1.0e7
SET tm_req_isost Tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material;

set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.00055 radius 0.25e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve
def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity   (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
; fvel_w = vel_w
command
    wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end

; ===================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
; final velocity of [w_vel] over approximately [w_cyc] cycles
; in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity   (float)
; cyc_w    - total number of cycles   (integer)
; stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
; fvel_w = vel_w
command
    wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end

; ===================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

;=====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

Cyc 60000
save dz21.SAV
;
return
;
;=====================================================================

;EOF: b4p.DVR
LOCATION Y-AXIS 100 MICRONS

new
set safe_conversion on
set random=1200
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ32'
title 'Four Point Bending Test Case 3 100 Microns Distance from Lower Ball'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5

; SET md_wEcfac=5.0
SET tm_req_isosstr=-1.0e7
SET tm_req_isosstr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.000485 radius 0.40e-4
delete ball range group Tunnel
crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand

command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;==================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;        cyc_w    - total number of cycles   (integer)
;        stages_w - number of intervals      (integer)
;
;        dv_w = vel_w / stages_w
;        niter_w = cyc_w / stages_w
;        vel_w = 0.0
;        loop ap_ii (1,stages_w)
;           vel_w = vel_w + dv_w
;        fvel_w = vel_w
;        command
;           wall id=10  yvel= @vel_w
;           cycle @niter_w
;        end_command
;        end_loop
;        end

;==================================================================

def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end
;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

 cyc 60000
 save dz323.SAV
 ;
 return
 ;=====================================================================;
;EOF: b4p.DVR
LOCATION Y-AXIS 200 MICRONS

new
set safe_conversion on
set random=1200
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ32'
title 'Four Point Bending Test Case 3 200 Microns Distance from Lower Ball'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5

; SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep
group Tunnel range circle center 0.000 -0.000385 radius 0.40e-4
delete ball range group Tunnel
crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;-----------------------------------------------------------------------------------
def acc_wall
,
; ----- Accelerate the wall in controlled fashion to achieve
; final velocity of [w_vel] over approximately [w_cyc] cycles
; in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
; fvel_w = vel_w
    command
    wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end

69
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=ywp(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz323.SAV
;
return
;==================================================================
LOCATION X-AXIS CENTER

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ41DincreaseLV0'
title 'Four Point Bending Test Case 3 Center Void'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.000565 radius 0.40e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;==================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
; final velocity of [w_vel] over approximately [w_cyc] cycles
; in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
;    fvel_w = vel_w
    command
        wall id=10 yvel= @vel_w
        cycle @niter_w
    end_command
end_loop
end
;==================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save DZ41DIncreaseLV0.SAV
;
return
;
;====================================================================
LOCATION X-AXIS RIGHT #1

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ41DincreaseLV1'
title 'Four Point Bending Test Case 3 Right#1 Void'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5

; SET md_wEcfac=5.0
; SET tm_req_isostr=-1.0e7
; SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0

; Specify parameters that define a parallel-bonded material
;

set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep
group Tunnel range circle center 0.0008750 -0.000565 radius 0.40e-4
delete ball range group Tunnel
crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand

command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
;  dv_w = vel_w / stages_w
;  niter_w = cyc_w / stages_w
;  vel_w = 0.0
; loop ap_ii (1,stages_w)
;  vel_w = vel_w + dv_w
;  fvel_w = vel_w
command
  wall id=10 yvel= @vel_w
  cycle @niter_w
end_command
end_loop
end

; def acc_wall
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

Cyc 60000
save DZ41DIncreaseLV1.SAV
;
return
;
; ================
; EOF: b4p.DVR
new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ41DincreaseLV2'
title 'Four Point Bending Test Case 3 Right#2 Void'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.0004375 -0.000565 radius 0.40e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
;    fvel_w = vel_w
    command
    wall id=10 _yvel= @vel_w
    cycle @niter_w
    end_command
end_loop
end

;==================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400  stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show


cyc 60000
save DZ41DIncreaseLV2.SAV
;
return
;
;===============================================================

;EOF: b4p.DVR
LOCATION X-AXIS RIGHT #3

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ41DincreaseLV3'
title 'Four Point Bending Test Case 3 Right#3 Void'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.00021875 -0.000565 radius 0.40e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;=================================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
    vel_w = vel_w + dv_w
    fvel_w = vel_w
    command
    wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end
;=================================================================================
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save DZ41DIncreaseLV3.SAV
;
return
;====================================================================

;EOF: b4p.DVR
QUANTITY DOUBLE VOID

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DZ41Dincrease22'
title 'Four Point Bending Test Case 4 Double Void Increase Distance

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
; SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set mdEc=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.000 -0.000565 radius 0.40e-4
group Tunnel 2 range circle center 0.000 -0.000400 radius 0.40e-4
delete ball range group Tunnel

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
endcommand

command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;==================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
;  dv_w = vel_w / stages_w
; niter_w = cyc_w / stages_w
; vel_w = 0.0
; loop ap_ii (1,stages_w)
;   vel_w = vel_w + dv_w
;  fvel_w = vel_w
; command
;    wall id=10  yvel= @vel_w
;    cycle @niter_w
; end_command
; end_loop
end

;==================================================================
```plaintext
def deflection
    wid=10
    wp=find_wall(wid)
    deflection=w_y(wp)
end

;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET  cyc_w=400  stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save DZ41DIncrease22.SAV
;
return
;
;====================================================================

;EOF: b4p.DVR
```
QUANTITY DOUBLE VOID DIFFERENT SIZE

set disk on
set echo on
set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS
set md_run_name='DZ2'
title 'Four Point Bending Test Case 4 Double Void Different Size'
set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
set md_wEcfac=5.0
set tm_req_isostr=-1.0e7
set tm_req_isostr_tol=0.50
set flt_def=3
set flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6
set tm_steps=100000
set et2_prep_saveall=1
et2_prep

group Tunnel range circle center 0.00035 -0.000565 radius 0.25e-4
group Tunnel2 range circle center -0.00035 -0.000565 radius 0.40e-4
delete ball range group Tunnel
delete ball range group Tunnel2

crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;==================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
; niter_w = cyc_w / stages_w
; vel_w = 0.0
; loop ap_ii (1,stages_w)
;     vel_w = vel_w + dv_w
;     fvel_w = vel_w
; command
;     wall id=10  yvel= @vel_w
;     cycle @niter_w
; end_command
; end_loop
end
;==================================================================
def deflection
  wid=10
  wp=find_wall(wid)
  deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12

plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show

plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show

plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save dz22.SAV

return

;====================================================================
=                          ;EOF: b4p.DVR
new
set safe_conversion on
set disk on
set echo on
set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='clustercase61'
title 'Four Point Bending Test Case 5 Clusters'
set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
SET pb_sn_mean_btn=1600e6 pb_sn_sdev_btn=400e6
SET pb_ss_mean_btn=3200e6 pb_ss_sdev_btn=800e6
SET pb_sn_mean_btn=1600e6 pb_sn_sdev_btn=400e6
SET pb_ss_mean_btn=3200e6 pb_ss_sdev_btn=800e6

set md_clusters=1;cluster exists
set extra ball 2:2 slots
set cl_size=10 cl_bslt=1;maximum number of balls per cluster
SET pb_sn_mean=1e30 pb_sn_sdev=0
SET pb_ss_mean=1e30 pb_ss_sdev=0

set tm_steps=100000

set et2_prep_saveall=1
et2_prep

def loadball
command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand

command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;=====================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
   vel_w = vel_w + dv_w
   fvel_w = vel_w
command
   wall id=10  yvel= @vel_w
   cycle @niter_w
end_command
end_loop
end

;=====================================================================
def deflection
wid=10
wp=find_wall(wid)
deflection=w_y(wp)
end

;=====================================================================
crk_init

delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save clustercase61.SAV
;
return
;======================================================================================
;EOF: b4p.DVR
new
set safe_conversion on
set random=1200
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DAA'
title 'Four Point Bending Test Case with no voids'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
; SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep
crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
ball id=500001 rad 0.000225 x -0.001225 y -0.00085
ball id=500002 rad 0.000225 x 0.001225 y -0.00085
ball id=500003 rad 0.000225 x -0.000725 y 0.00085
ball id=500004 rad 0.000225 x 0.000725 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

; ===================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
; final velocity of [w_vel] over approximately [w_cyc] cycles
; in [w_stages] stages.
;
; INPUT: vel_w    - final platen velocity    (float)
;        cyc_w    - total number of cycles   (integer)
;        stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
  vel_w = vel_w + dv_w
  fvel_w = vel_w
  command
    wall id=10 yvel= @vel_w
cycle @niter_w
end_command
end_loop
end

; ===================================================================
def deflection
wid=10
wp=find_wall(wid)
deflection=w_y(wp)
end

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save daa.SAV
;
return
;====================================================================
=EOF: b4p.DVR
new
set safe_conversion on
set random=1200
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DAA'
title 'Four Point Bending Test Case with no voids'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
;
SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;
set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep
crk_init
delete wall 1
delete wall 2
delete wall 3
delete wall 4

solve

def loadball

command
  ball id=500001 rad 0.000225 x -0.001225 y -0.00085
  ball id=500002 rad 0.000225 x 0.001225 y -0.00085
  ball id=500003 rad 0.000225 x -0.000725 y 0.00085
  ball id=500004 rad 0.000225 x 0.000725 y 0.00085
  wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
  prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
endcommand

end

; ==------------------------------------------------------------------

def acc_wall

; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
;   dv_w = vel_w / stages_w
;   niter_w = cyc_w / stages_w
;   vel_w = 0.0
loop ap_ii (1,stages_w)
  vel_w = vel_w + dv_w
  fvel_w = vel_w
  command
    wall id=10 yvel= @vel_w
cycle @niter_w
  end_command
end_loop
end

; ==------------------------------------------------------------------

def deflection
wid=10
wp=find_wall(wid)
deflection=w_y(wp)
end

;====================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET cyc_w=400 stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save daa.SAV
;
return
;====================================================================

;EOF: b4p.DVR
INDENTATION WITH SIMPLE SAMPLE

new
set safe_conversion on
set disk on
set echo on

set gen_error off
call md_bending.FIS
call et2.FIS
call flt.FIS
call cluster.FIS
call crk.FIS
call fishcall.FIS

set md_run_name='DAAno'
title 'Indentation Test with no voids'

set et2_xlen=0.0035 et2_ylen=0.00125
set et2_radius_ratio=2 et2_rlo=.5e-5
; SET md_wEcfac=5.0
SET tm_req_isostr=-1.0e7
SET tm_req_isostr_tol=0.50
SET flt_def=3
SET flt_remain=0.0
; Specify parameters that define a parallel-bonded material
;

set md_add_pbonds=1
set md_dens=3200
set md_Ec=220e9 md_knoverks=1.275
set pb_radmult=1 pb_Ec=220e9 pb_knoverks=1.275
set md_fric=0.4
set pb_sn_mean=1600e6 pb_sn_sdev=400e6
set pb_ss_mean=3200e6 pb_ss_sdev=800e6

set tm_steps=100000

set et2_prep_saveall=1
et2_prep
crk_init
delete wall 2
solve
def loadball

command
ball id=500004 rad 0.000225 x 0.000 y 0.00085
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 nodes (-0.0025,0.001075) (0.0025,0.001075)
endcommand
command
prop dens=3200 kn=1e11 ks=1e11 fric=0.0 ra id=500001,500004
wall id=10 ks 1e11 kn 1e11 fric 0.0
endcommand
end

;==========================================================================================
def acc_wall
;
; ----- Accelerate the wall in controlled fashion to achieve
;       final velocity of [w_vel] over approximately [w_cyc] cycles
;       in [w_stages] stages.
;
; INPUT:  vel_w    - final platen velocity    (float)
;         cyc_w    - total number of cycles   (integer)
;         stages_w - number of intervals      (integer)
;
; dv_w = vel_w / stages_w
niter_w = cyc_w / stages_w
vel_w = 0.0
loop ap_ii (1,stages_w)
  vel_w = vel_w + dv_w
;  fvel_w = vel_w
command
  wall id=10  yvel= @vel_w
  cycle @niter_w
end_command
end_loop
end

;==========================================================================================
def deflection
wid=10
wp=find_wall(wid)
deflection=w_y(wp)
end
;==========================================================================================

loadball
plot show
fix x range id=500001,500004
property xvel=0 range id=500001,500004
fix y range id=500001,500002
property yvel=0 range id=500001,500002
free spin range id=500001,500004

set vel_w=-2.0
SET  cyc_w=400  stages_w=10
acc_wall
deflection

hist id 11 wall yforce id 10
hist id 12 deflection
set display his 11 ; add hist-11 to the status report while cycling
set display his 12
;
plot create Load
plot add hist 11
plot set title text 'Load vs step'
plot show
;
plot create Displacement
plot add hist 12
plot set title text 'Displacement vs Step'
plot show
;
plot create crackfigure
plot add fish crk_item
plot show

cyc 60000
save daano.SAV
;
return
;=============================================================================
;EOF: b4p.DVR
Vita

Ana Laura Quezada Lara was born in Ciudad Juarez, Mexico, on March 29, 1986. She attended Instituto Tecnologico de Estudios Superiores de Monterrey at her hometown and in May 2008 received the degree of Bachelor of Science in Industrial Engineering. During college on June 2006 she started a co-op position at Valeo Motors and Actuators developing new projects in the purchasing department. After her experience at Valeo she started working for Delphi Mexico Technical Center on September 2007 up to date as a Hazmat Packaging Engineer developing and validating new packaging for the growing business of power electronics. She entered the University of Texas at El Paso on August 2008 and is a candidate for the degree of Master of Science in Industrial Engineering.

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This thesis/dissertation was typed by Ana Laura Quezada Lara.