Modeling of Light Body Ceramic Armor Using Hertzian Indentation

By

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Introduction:

With the wars in Iraq and Afghanistan placing U.S. soldiers in harms way, there is immediate need to developing tough yet lightweight body armors that would defeat rifle-fired armor-piercing (AP) bullets. Current body armor uses relatively heavy layer of ceramic material in order to absorb a ballistic impact. Such heavy body armor reduces a soldier’s mobility when it is most needed.

Since 2003, government funding of armor research and development has increased significantly. For example, General Dynamics Armament & Technical Products was recently warded up to $103 M to develop and install Abrams Tanks reactive armor tiles by the U.S. Army Tank Automotive & Armaments Command, while Ceradyne Inc. received a new 60-month government contract for enhanced side ballistic insert body armor worth $612 M [1]. These are but two small examples of the multitude of capital being spent on this area of research and development. With regards to professional conferences and specifically the one this PI attends on an annual basis, focused sessions on armor ceramics became part of the International Conference & Exposition on Advanced Ceramics and Composites annual meeting in 2003.

In order to design lightweight ceramic body armor without compromising their integrity, it is essential to understand how they fail when subjected to ballistic impact. It has been experimentally shown by previous investigators [2] that the process of pushing a hard ball (made from materials such as diamond, silicon carbide, or steel) to statically indent a ceramic armor plate (made from materials such as silicon carbide, alumina, or boron carbide) has much in common with the damage induced due to ballistic impact loads. Therefore, the objective of this proposal is to utilize advanced and refined computer simulations and probabilistic failure theories of Hertzian indentation tests to analyze and predict the contact stresses and failure in armor ceramics.

A Hertzian indentation test simply involves pushing a hard ball (representing the projectile) against a plate (representing the armor material) and measuring the force at which cracking and
subsequent damage events begin. By properly choosing an indenter ball diameter and material, similar contact stresses and cracking to those generated during actual ballistic impact can be replicated in the armor material.

Mark Wilkins, a pioneer in the field of computational ceramic armor modeling, discovered early on (1968) that a lightweight system required conflicting material demands [3-4]. On one hand a hard plate (ceramic like SiC) is needed to erode and decelerate the bullet, while a ductile substrate plate (metal like Aluminum) is needed to stop and absorb the remaining energy of the eroded bullet. Figure 1 shows an experiment conducted at Southwest Research Institute displaying the response of armor–piercing (AP) bullet against a Boron Carbide (B₄C) ceramic tile glued to an aluminum substrate. Figure 1-a shows a front view of the damage to the ceramic plate, while the side view in figure1-b highlights the deformation in the aluminum substrate plate. Figure 2 displays a series of high-speed photographs during a test where an AP bullet was launched at a ceramic/metal armor system with a muzzle velocity of about 825 m/s. It is interesting to observe how the bullet begins to erode as it strikes the ceramic B₄C plate, followed by the deformation in the Aluminum plate as expected.

Fig.1: Post-test photograph of impact of AP bullet against ceramic/aluminum target [reference 4].

Fig.2: Flash radiographs of AP bullet impacting a 7.62-mm B₄C/6.6-mm 6061-T6 Aluminum target at an approximate velocity of 825 m/s [reference 4].
While complex dynamical models may succeed in predicting failure for ceramic armor, they are computationally intensive and require extensive testing, and thus cost, to measure the necessary static and dynamic material parameters. Such inefficiencies translate into high cost, difficulty of executing the models due to their complexities, and delayed time to market. As stated previously, it has been observed and proven that a simple static Hertzian hardness test (Fig. 3) where a ball with proper material and diameter is slowly indented against the ceramic armor can be used to analyze how such materials fail under ballistic loading.

![Figure 3: Schematic of Hertzian indentation test.](image)

**2) Finite Element Analysis (FEA) Modeling:**

FEA stress analyses for a multilaminate glass disk, with and without residual stresses due to thermal mismatch, were performed in this study. Two boundary conditions were considered: a) ball-on-ring (BOR), and b) elastic foundation (rollers). Subsequently, probabilistic design system (PDS) analyses were conducted for the four different cases whereby up to 7 geometric, material, and thermal load parameters were varied to minimize two response variables. These two response variables are the maximum tensile contact stress at the free surface of the top glass layer ($S_{1\_contact}$) and the maximum bending stress at the bottom surface of the top glass layer ($S_{1\_bend}$). The PDS study yielded sensitivity plots showing which random input variables most affect these two stresses.

Figure 4 shows the cross sectional layout for the multilaminate glass disk with colors corresponding to material sequence. In this schematic, the turquoise layers are glass, purple layers are polyurethane, while the pink layer is polycarbonate. Model dimensions are listed in Table 1. Table 2 contains the thermomechanical properties for the four materials involved in the model.
Figure 4: Cross sectional layer layout for ball-on-ring (BOR) multilaminate disk with colors corresponding to material sequence. Turquoise layers are glass, purple layers are polyurethane, while the pink layer is polycarbonate.

Table 1: Model dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Magnitude (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>top glass layer thickness</td>
<td>10</td>
</tr>
<tr>
<td>1st polyurethane layer thickness</td>
<td>1.27</td>
</tr>
<tr>
<td>2nd glass layer thickness</td>
<td>10</td>
</tr>
<tr>
<td>2nd polyurethane layer thickness</td>
<td>2.54</td>
</tr>
<tr>
<td>polycarbonate substrate thickness</td>
<td>6.35</td>
</tr>
<tr>
<td>ball diameter</td>
<td>6.35</td>
</tr>
<tr>
<td>ring support diameter</td>
<td>249</td>
</tr>
<tr>
<td>disk diameter</td>
<td>356.6</td>
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</table>

Table 2: Thermomechanical material properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>E (GPa)</th>
<th>Poisson’s ratio</th>
<th>CTE Ppm/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>70</td>
<td>0.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Steel (indenter)</td>
<td>200</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Polyurethane</td>
<td>0.25</td>
<td>0.45</td>
<td>101</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>2.8</td>
<td>0.4</td>
<td>68</td>
</tr>
</tbody>
</table>

Plane82 axisymmetric elements were used to simulate the model and conduct the thermomechanical analyses. Figure 5 shows the mesh distribution used in the simulation which contained 5352 elements and 15854 nodes.
Figure 5: Mesh distribution showing plane82 axisymmetric elements. The mesh contains 5352 elements and 15854 nodes.

Figure 6 displays the first principal residual stress distribution in the entire glass laminate due to a processing temperature drop of 100 °C. Figure 7 shows the first principal residual stress distribution in the top glass layer due to the same temperature differential. Figures 8 and 9 highlight the principal contact stress (S1_contact) and the principal bending stress (S1_bend) in the top glass layer.

Figure 6: Principal residual stress distribution in the multilaminate glass disk due to temperature drop of 100 °C.
Figure 7: Principal residual stress distribution in the top glass layer due to temperature differential of 100 C.

Figure 8: Principal stress distribution in the contact region of the top glass layer due to combined contact and thermal loading with ball-on-ring configuration. Maximum stress in this plot corresponds to S1_contact.
Figure 9: Principal stress distribution in the top glass layer due to combined contact and thermal loading with ball-on-ring configuration. Maximum stress in this plot corresponds to $S_{1\_bend}$.

Figure 10 displays a comparison between the classic Hertzian equation, FEA results due to ball contact only, and FEA results due to ball contact and thermal residual stresses for maximum contact stress as function of load at the free surface of the top glass layer with BOR. Also shown in figure 10, is the maximum bending stresses at the bottom surface of the top glass layer due to ball contact. The FEA contact stresses are lower than what is predicted by the Hertzian equation due to the multiple compliant layers and the flexible BOR support.
Figure 10: Comparison between Hertzian classic equation, FEA results due to ball contact only, and FEA results due to ball contact and thermal residual stresses for maximum tensile contact stress at the free surface of the top glass layer with BOR configuration. Also shown, are the maximum bending stresses at the bottom surface of the top glass layer due to ball contact only, and due to combined contact and residual stresses.

**Probabilistic Design Analyses for the Multilaminate Glass Plate:**

The probabilistic design system (PDS), a capability provided within the ANSYS FEA code, permits performing Monte Carlo simulations with multiple input random variables. Geometric, material, and load parameters can be assumed to vary by assigning statistical distribution functions to them. Response variables are defined so that the device can be optimized by minimizing or maximizing them. The PDS analysis can then be used to perform sensitivity analysis to determine which random input variables should be altered, and how, in order to optimize the selected response variables.

In this analysis, two response random variables were defined. These are:

1) Maximum principal contact stress at the free surface of the top glass layer ($S_1_{contact}$)
2) Maximum principal bend stress at the bottom surface of the top glass layer ($S_1_{bend}$)

Two boundary conditions were considered:
1) ball-on-ring configuration
2) ball on elastic foundation configuration.

Hence, the following four PDS scenarios were performed:

1) Isothermal ball-on-ring case (no residual stresses due to processing)
2) Thermomechanical ball-on-ring case (includes residual stresses due to processing)
3) Isothermal elastic foundation case (no residual stresses due to processing)
4) Thermomechanical elastic foundation case (includes residual stresses due to processing)

The goal is to determine which geometric, material, and thermal load parameters most influence $S_{1\_contact}$ and $S_{1\_bend}$.

In these PDS analyses, up to 7 material, geometric, and processing temperature parameters were assumed to be random input variables (RIV). For example, glass and polyurethane layer thicknesses were assumed to be changeable and hence set as RIV. In the two isothermal PDS cases, the processing temperature was not included and thus 6 RIV were utilized. For the two thermomechanical cases, the processing temperature was included leading to 7 RIV in these analyses.

Table 3 lists all the input random variables used in the PDS analyses. All these variables were defined to vary using uniform statistical distribution functions. Figure 11 shows an example of such uniform distribution function for the thickness of the top glass layer.

Table 3: Random input variable specifications

<table>
<thead>
<tr>
<th>Random input variable</th>
<th>Distribution</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>comments</th>
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<tbody>
<tr>
<td><strong>Material Random Variables</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{_indenter}$ (GPa)</td>
<td>uniform</td>
<td>200</td>
<td>650</td>
<td>Representing steel to tungsten carbide indenters.</td>
</tr>
<tr>
<td>$E_{_glass}$ (GPa)</td>
<td>uniform</td>
<td>60</td>
<td>75</td>
<td>Different grades of glass</td>
</tr>
<tr>
<td><strong>Geometric Random Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_{t1}$ (mm)</td>
<td>uniform</td>
<td>5</td>
<td>15</td>
<td>Range of thicknesses for top glass layer</td>
</tr>
<tr>
<td>$h_{t2}$ (mm)</td>
<td>uniform</td>
<td>0.625</td>
<td>2.54</td>
<td>Range of thicknesses for 1st polyurethane layer</td>
</tr>
<tr>
<td>$h_{t3}$ (mm)</td>
<td>uniform</td>
<td>5</td>
<td>15</td>
<td>Range of thicknesses for second glass layer</td>
</tr>
<tr>
<td>$h_{t4}$ (mm)</td>
<td>uniform</td>
<td>0.625</td>
<td>2.54</td>
<td>Range of thicknesses for 2nd polyurethane layer</td>
</tr>
<tr>
<td><strong>Thermal Load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAMB</td>
<td>uniform</td>
<td>-140</td>
<td>-60</td>
<td>Temperature difference between processing and service temperatures</td>
</tr>
</tbody>
</table>
1) Isothermal ball-on-ring case (no residual stresses due to processing):

The ANSYS PDS analysis was performed using 80 samples.

Figure 12 shows the principal contact stress at the free surface of the top glass layer (S1_contact) as function of 80 Monte Carlo-Latin Hyper cube simulations. Figure 13 displays the cumulative probability distribution with 95% confidence limits for S1_contact based on 80 Monte Carlo-Latin Hyper cube simulations. As can be seen from these two figures and based on varying the 6 RIVs as described in table 3, the contact stress can range anywhere between 883 and 1525 MPa.

Figure 14 shows the principal bending stress at the bottom surface of the top glass layer (S1_bend) as function of the 80 Monte Carlo-Latin Hyper cube simulations. Figure 15 displays the cumulative probability distribution with 95% confidence limits for S1_bend based on 80 Monte Carlo-Latin Hyper cube simulations. As can be seen from these two figures and based on varying the 6 RIVs as described in table 3, the bending stress can range anywhere between 37 and 293 MPa.

Figure 16 is the sensitivity plot highlighting the relative importance of the random input variables on S1_contact. It can be seen from this figure that only the thickness of the top glass layer significantly affects the contact stress S1_contact, whereby as the glass thickness increases so does the contact stress.
Figure 17 is the sensitivity plot highlighting the relative importance of the random input variables on S1_bend. It can be seen from this figure that only the thickness of the top glass layer significantly affects the bending stress S1_bend, whereby as the glass thickness increases, the bending stress decreases.

Similar observations were made by Lawn et al. (5) when they tested bilayer disks under indentation. They noted that for large top layer glass thickness and small indenter radius, the tensile stresses concentrate outside the contact in the top surface and have the form of the classic Hertzian stress field. For small top layer glass thickness and large indenter radius, the tensile stresses are transferred to the bottom surface of the top layer and assume the form of flexing a plate on compliant substrate. These observations are identical to the PDS results as summarized above. In our analysis, we chose not to include the ball radius as a RIV for two reasons. First, the influence of the ball diameter on contact stress and bending stress is well understood and thus nothing will be gained by including it as a RIV. And two, had we included the indenter diameter into the analysis it might have dominated the other variables.

**Figure 12**: Principal contact stress at the free surface of the top glass layer (S1_contact) as function of the 80 Monte Carlo-Latin Hyper cube simulations.
Figure 13: Cumulative probability distribution with 95% confidence bounds for the principal contact stress at the free surface of the top glass layer (S1_contact) based on 80 Monte Carlo-Latin Hyper cube simulations.

Figure 14: Principal bending stress in the top glass layer (S1_bend) as function of the 80 Monte Carlo-Latin Hyper cube simulations.
Figure 15: Cumulative probability distribution with 95% confidence limits for the principal bending stress in the top glass layer (S1_bend) based on 80 Monte Carlo-Latin Hyper cube simulations.

Figure 16: Sensitivity plot for the principal contact stress at the free surface of the top glass layer (S1_contact).
Figure 17: Sensitivity plot for the principal bending stress at the bottom surface of the top glass layer (S1_bend).

2) Thermomechanical ball-on-ring case (includes residual stresses due to processing):

The ANSYS PDS analysis was performed using 42 samples.

Figure 18 shows the principal contact stress at the free surface of the top glass layer (S1_contact) as function of 42 Monte Carlo-Latin Hyper cube simulations. As can be seen from this figure and based on varying the 7 RIVs as described in table 3, the contact stress can range anywhere between 877 and 1495 MPa.

Figure 19 shows the principal bending stress at the bottom surface of the top glass layer (S1_bend) as function of 42 Monte Carlo-Latin Hyper cube simulations. As can be seen from these two figures and based on varying the 7 RIVs as described in table 3, the bending stress can range anywhere between 18.4 and 208.4 MPa.

No sensitivities were found to be significant for S1_contact and thus no sensitivity plot was generated by the ANSYS PDS module.

Figure 20 is the sensitivity plot highlighting the relative importance of the random input variables on the S1_bend. It can be seen from this figure that only the thickness of the top glass layer significantly affects the bending stress S1_bend, whereby as the glass thickness increases, the bending stress decreases.
In order to understand the sensitivity results, as to why the thickness of the top glass layer (ht1) affects only S1_bend but not S1_contact, several FEA runs were performed. In these simulations, ht1 in the multilaminate model was varied between 6 and 14 mm by 2 mm intervals and loaded using 6.35 mm diameter steel indenter, while keeping the total glass thickness (ht1 +ht3) equal to 20 mm. Figures 21 and 22 show the principal contact and bending stresses as function of load and ht1, respectively. It is to be noted that all sensitivity analyses in this report were performed for contact and bending stresses corresponding to 5000 N indentation load. These stress values are highlighted in figures 21 and 22 by inclosing them within rectangles at 5000 N.

As can be seen from figure 21, no pattern or great variation in S1_contact as ht1 varies emerges. This explains the PDS results whereby no S1_contact sensitivity to ht1 was found. Conversely, figure 21 displays clear sensitivity of S1_bend to ht1. This figure shows that as ht1 increases, S1_bend decreases. This explains the PDS results whereby S1_bend was found to inversely depend in ht1.

Figure 18: Principal contact stress at the free surface of the top glass layer (S1_contact) as function of the 42 Monte Carlo-Latin Hyper cube simulations.
Figure 19: Principal bending stress in the top glass layer ($S_{1\_bend}$) as function of the 80 Monte Carlo-Latin Hyper cube simulations.

Figure 20: Sensitivity plot for the principal bending stress at the bottom surface of the top glass layer ($S_{1\_bend}$).

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mean</td>
<td>0.83325E+02</td>
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<tr>
<td>Standard Deviation</td>
<td>0.54323E+02</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.90412E+00</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-0.31212E+00</td>
</tr>
<tr>
<td>Min</td>
<td>0.18414E+02</td>
</tr>
<tr>
<td>Max</td>
<td>0.20839E+03</td>
</tr>
</tbody>
</table>

Significant:
- $M_{1}$

Insignificant:
- $M_{3}$
- $M_{2}$
- $M_{4}$
- $E_{3}$
- $E_{1}$
- $T_{AM}$

Significance level: 2.5%.
Figure 21: Principal contact stress as function of load and thickness of top glass layer using a 6.35 mm diameter steel indenter. Sensitivity analysis was performed for the stresses corresponding to 5000 N indentation load (in box).

Figure 22: Principal bending stress as function of load and thickness of top glass layer using a 6.35 mm diameter steel indenter. Sensitivity analysis was performed for the stresses corresponding to 5000 N indentation load (in box).
3) Isothermal ball-on-elastic foundation case (no residual stresses due to processing):

The ANSYS PDS analysis was performed using 80 samples.

Figure 23 shows the principal contact stress at the free surface of the top glass layer (S1_contact) as function of 80 Monte Carlo-Latin Hyper cube simulations. As can be seen from this figure and based on varying the 6 RIVs as described in table 3, the contact stress can range anywhere between 920 and 1476 MPa.

Figure 24 shows the principal bending stress at the bottom surface of the top glass layer (S1_bend) as function of 80 Monte Carlo-Latin Hyper cube simulations. As can be seen from these two figures and based on varying the 6 RIVs as described in table 3, the bending stress can range anywhere between 29.3 and 260.9 MPa.

Figure 25 is the sensitivity plot highlighting the relative importance of the random input variables on S1_contact. It can be seen from this figure that the elastic moduli of the indenter and glass layer significantly affect the contact stress S1_contact, whereby as these two moduli increase so will the contact stress. Here, the thickness of the glass layer effect on S1_contact becomes insignificant since the bottom surface of the multilaminate disk is entirely restrained.

Figure 26 is the sensitivity plot highlighting the relative importance of the random input variables on the S1_bend. It can be seen from this figure that only the thickness of the top glass layer significantly affects the bending stress S1_bend, whereby as the glass thickness increases, the bending stress decreases.
Figure 23: Principal contact stress at the free surface of the top glass layer (S1_contact) as function of the 80 Monte Carlo-Latin Hyper cube simulations.

Figure 24: Principal bending stress in the top glass layer (S1_bend) as function of the 80 Monte Carlo-Latin Hyper cube simulations.
Figure 25: Sensitivity plot for the principal contact stress at the free surface of the top glass layer (S1_contact).

Figure 26: Sensitivity plot for the principal bending stress at the bottom surface of the top glass layer (S1_bend).
4) Thermomechanical ball-on-elastic foundation case (includes residual stresses due to processing):

The ANSYS PDS analysis was performed using 60 samples.

Figure 27 shows the principal contact stress at the free surface of the top glass layer (S1_contact) as function of 60 Monte Carlo-Latin Hyper cube simulations. As can be seen from this figure and based on varying the 7 RIVs as described in table 3, the contact stress can range anywhere between 613.4 and 1712 MPa.

Figure 28 shows the principal bending stress at the bottom surface of the top glass layer (S1_bend) as function of 60 Monte Carlo-Latin Hyper cube simulations. As can be seen from these two figures and based on varying the 7 RIVs as described in table 3, the bending stress can range anywhere between 28.4 and 280.6 MPa.

No sensitivities were found to be significant for S1_contact and thus no sensitivity plot was generated by ANSYS PDS module.

Figure 29 is the sensitivity plot highlighting the relative importance of the random input variables on the S1_bend. It can be seen from this figure that only the thickness of the top glass layer significantly affects the bending stress S1_bend, whereby as the glass thickness increases, the bending stress decreases.

Conclusions:

1) Residual stresses do not significantly influence S1_contact and S1_bend. This is because the residual stress at the top surface is minute compared to S1_contact, and is approximately zero at the bottom surface where S1_bend exists.

2) The major variable influencing S1_bend is the thickness of the top glass layer. As this thickness increases, S1_bend decreases.

3) For the BOR isothermal case, as the thickness of the top glass layer increases, S1_contact increases.

4) For the elastic foundation isothermal case, two parameters influence S1_contact. These are the elastic moduli of the indenter and the top glass layer. As these two parameters increase so will S1_contact.
Figure 27: Principal contact stress at the free surface of the top glass layer (S1_contact) as function of the 60 Monte Carlo-Latin Hyper cube simulations.

Figure 28: Principal bending stress in the top glass layer (S1_bend) as function of the 60 Monte Carlo-Latin Hyper cube simulations.
Figure 29: Sensitivity plot for the principal bending stress at the bottom surface of the top glass layer (S1\textunderscore bend).

References: