DETERMINATION OF THE MECHANICAL BEHAVIOUR OF A CERAMIC GLASS COMPOSITE BY FINITE ELEMENT METHOD

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ABSTRACT
The constant advances in the industry originate from the need to develop solutions for a variety of applications. Mechanical Engineering has introduced innovations with regard to the science of materials subjected to various efforts. Recent studies demonstrate the potential of some classes of materials, special emphasis on ceramics. In this paper, we are going to study primarily the ceramic glass sub-class through analysis of Zerodur®. Zerodur® is a trade name given to an inorganic material with low thermal expansion, widely used in equipment subjected to large temperature variations, where it is necessary to maintain good shape and geometry precision. It has high surface hardness and hence fragility when subjected to tensile. In order to enhance the mechanical characteristics of Zerodur® is proposed to merge the same with other materials (composite). With the aid of finite element method makes it possible to analyze the global behaviour of the composite when subjected to external stresses. In this paper, we used the commercial finite element solver MARC™ on numerical analysis of computational structures Zerodur® - Steel. The main objective of this work is to simulate the behaviour of the composite test by three point bending. Subsequently, we intend to analyze the mechanical stiffness and implement models with crack strain.

Keywords: Composite, Finite Elements, Numeric Simulation, Zerodur®.

1. INTRODUCTION
The constant search for materials with high resistance to various conditions boosts search for compounds that are resistant to adverse conditions. However, due to the high degree of complexity of new materials, characterize their mechanical behaviour is always difficult and costly mainly because there is a difference between the mechanical properties of the constituent phases and the resulting compound. The coupling between numerical models and macroscopic analysis of the structure has been an effective alternative in the design of mechanical structures and minimize failures.

In this instance, it has been used discrete models finite element method (FEM) together with the concepts of continuum mechanics for the evaluation of damage in a structure. These approaches have been developed, both for the analysis of structural failures in brittle materials, and for ductile materials. However, the correct incorporation of mechanical and phenomenological aspects inherent in the design and the failure mechanisms are a key factor for the success and effectiveness of these predictive methodologies applicable to the numerical analysis of the mechanical integrity of a broad class of structural components and of different materials [1, 2]. A series of materials is highlighted in terms of their tribological properties, among them are ceramic, especially in conditions in which the material requires good wear resistance, chemical attack and impact at elevated temperatures.

The ceramic materials are basically composed of metallic and non-metallic elements by ionic bonds and/or covalent bonds. They are classified as crystalline, amorphous or glass-ceramic. In this work, we are going to study the mechanical behaviour of a glass ceramic material called commercially Zerodur®, when subjected to the numerical test of three point bending. The methodology was based on numerical analysis (FEM) of composites with the matrix phase as glass ceramic and dispersed phase as small longitudinal bars of Steel. This arrangement aims to improve the mechanical behaviour of the glass ceramic when subjected to the numerical bending test. The mechanical stiffness of the material was evaluated according to transverse displacement values.

The simulations proposed in this paper using discrete models based on the MEF, which is a reliable technique for numerical analysis of stresses and strain in the simulation of various engineering problems. This method has been widely used to simulate and solve many nonlinear problems in the areas of structural instability, dynamical systems and thermo-fluid dynamic, electromagnetic systems and metal forming. These numerical simulations were performed on the commercial finite element solver MARC™[3].
2. THE GLASS CERAMIC (ZERODUR®)

In 1968, Schott Glass Technologies Inc.© developed the Zerodur® [4]. This new material is designed for applications where temperature changes are inevitable and can negatively influence the size and critical dimensions of the accuracies. It is a machine able glass ceramic material with low thermal expansion, non-porous, isotropic and widely used in applications where temperature variations occur. Due to its high quality and performance, this material has been used in several branches of modern industry as in the optical elements for lithography equipment, mechanical parts for metrology equipment and high precision, large mirrors for astronomical telescopes and standards for technology precision measurement, Figure 1. However, this glass ceramic has a low modulus of elasticity, consequently, low structural rigidity, and a typical brittle behaviour of ceramics, limiting its use.

![Figure 1. Measurement Standards made from Zerodur®.](image)

Production of this glass ceramic comes from modern methods of crystal and optical technology. The crystals are melted, refined, homogenized and finally resigned. After subsequent cooking decreases the pressure to complete treatment of the crystalline core. This process is accompanied by an accuracy ceramization, during which the crystals are transformed into a glass ceramic by controlled crystallization volume [4]. During this treatment, centres are formed inside the glass, and there is the appearance of crystals at high temperatures. The resulting material is transparent and clear, with the following properties [5]:

- Very low thermal expansion coefficient;
- Good homogeneity;
- High internal quality;
- Good surface finish;
- High chemical stability.

Basically, this glass ceramic is formed by oxides (Li2O, SiO2, Al2O3), with a density of 2.53 g/cm³, the thermal conductivity of 1.6 W / mK and coefficient of thermal expansion lower 0.10 x10^{-6} / K [6]. It also has good process ability, in other words, it is easy to handle during manufacturing despite having a temperature range of synthesis that goes from 700 °C to 1000 °C [7]. The main feature of Zerodur® is the presence of an amorphous phase that has a positive thermal expansion (expansion) and a crystalline phase that has a negative thermal expansion (contraction), which gives a low rate of variation in size when subjected to large temperature variations. This feature is obtained by nucleation well defined and appropriate conditions of crystallization, which makes itself a material with low thermal expansion coefficient. In certain ranges of temperature coefficient of thermal expansion may be approximately zero or even slightly negative, depending on the process used ceramization [8].

Quantitatively it is composed of 70 to 78% crystalline phase, with high solution of quartz, which gives the surface more transparent and becomes it more robust. This phase has approximately eleven nanometres in diameter, which makes it very hard, difficult to penetrate and low reflection. On the other hand, if part of this phase also receives an array of fused silica is transmitted greater protection [9]. When referring to its transparency, Zerodur® is indicated a
degree of transparency to it, which is defined by ultraviolet lithography. It is a technique that analyzes how the amorphous phase interferes in transparency, being possible improves the percentage of the two phases to establish more precisely the desired degree of purity [10].

3. METHODOLOGY

3.1. Bending Testing
To evaluate the mechanical strength of brittle materials such as, for example, ceramic material is commonly used for bending test of three points. In this essay, a prismatic specimen is supported at two fixed supports and is subjected to a load $P$ at the centre of the bar, as Figure 2.

![Figure 2. illustration of three points bending testing.](image)

To define the dimensions of the specimens of the bending test was used as the basis of the technical references ASTM E399 [11]. The relations defined in this standard are illustrated in Figure 2, where $L$ is the distance between supports and $P$ is the applied load. In this work, the composite has as matrix phase the glass ceramic and as the dispersed phase carbon steel bars, arranged as shown in Figures 3 and 4. The carbon steel bars have total surface area of 0.00142 m². It is expected that these settings to the dispersed phase to improve the mechanical stiffness of the composite as bend, when compared with the behaviour of a beam of the same dimensions made with only the glass ceramic material, Figure 5. It is also expected that the metal bars have a greater contribution to resist the tensile stresses from the bending of the beam.

![Figure 3. Composite made of glass ceramic and steel – numerical arrangement with two bars.](image)
Figure 4. Composite made of glass ceramic and steel—numerical arrangement with three bars.

Figure 5. Numerical mesh - Cantilever beam made of glass ceramic (100% Zerodur®).
It was used finite element numerical models to simulate the mechanical behaviour in bending. Initially, it was simulated the behaviour of a specimen made of the glass ceramic material and then represented to the composite. The numerical models were constructed using three-dimensional hexagonal elements with eight nodes, in order that the cross section of the bars has symmetry. It was obtained the displacement in the middle of the beam ($Y_{max}$) for different configurations of composite. Then, it was evaluated the mechanical stiffness of the joint. Table 1 shows the mechanical properties adopted for the ceramic glass and the steel.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elasticity modulus ($E$)</th>
<th>Poisson Coefficient ($\nu$)</th>
</tr>
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<tbody>
<tr>
<td>Zerodur®</td>
<td>91 GPa</td>
<td>0,24</td>
</tr>
<tr>
<td>Aço</td>
<td>210 GPa</td>
<td>0,300</td>
</tr>
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</table>

### 3.2. Cracking Strain Model

The simulate of the behaviour of glass ceramic during the bending testing was incorporated into the numerical analysis by a model with some mechanisms of damage processes through a constitutive relation based on classical models of continuum mechanics using a uniaxial curve of tension in function of strain, known as cracking strain model, Figure 6.

![Uniaxial diagram of stress in function of strain for the cracking strain model](image)

For tensile stresses, this model allows an elastic behaviour until the breaking point ($\sigma_c$). Reaching this limit, it is assumed the cracking of the material in the direction normal to the Maximum Principal Stress. After the formation of first crack, the model is replaced by an orthotropic behaviour. This model allows the formation of a maximum of three mutually perpendicular cracks, where the three principal stresses exceeding the material tearing. After the first crack nucleation, the second crack can be created perpendicular to the first and a third crack would form perpendicular the both. The model also allows incorporation of a decrease in the resistance behaviour of the structure after formation of the first cracks described by a softening parameter of the elastic modulus ($E_s$). This parameter, which can be determined from the material properties and geometry of the mesh used to prevent tensile stress from the numerical model at one point cracked tends rapidly to zero after the normal stress exceeded its maximum tensile strength [2-3, 13].

The Zerodur® presents a behaviour that resembles this model crack strain, in other words, this material has low tensile strength, but has good compressive strength and may also has large plastic deformation with hardening under compression [13]. Input these parameters for the model are presented in Table 2. By successive numerical analysis for calibration of the softening modulus, it was found that the same can be estimated as one hundredth of the value of Elasticity modulus of Zerodur® [13].
Table 2. E, Es, σcr, εcrush input parameters [12-14].

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<tr>
<td>E</td>
<td>91</td>
<td>9.1</td>
<td>98</td>
</tr>
<tr>
<td>Es</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σcr</td>
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<td></td>
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<tr>
<td>εcrush</td>
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4. RESULTS AND DISCUSSIONS

Figure 7 shows the boundary conditions of the numerical model subjected to bending testing. In this model, it was restricted the displacement at the supports in the directions x, y and z. After that, it applied a total load of 500 N at mid-span of sample.

The result of the numerical beam model made of glass ceramic was compared with the analytical results obtained from the equation of the elastic displacement of a bi supported with a load applied at mid-span (Euler-Bernoulli equation), Equation 1[15]. In this equation, \( Y_{\text{max}} \) is the maximum displacement of the bar that occurs at mid-span. \( P \) is the applied load and \( l \) is the distance between supports. Also, \( E \) is the Elasticity modulus of the material and \( I \) the moment of inertia of cross section. For this model, it was adopted the following values: \( l = 4.8 \text{ m} \), \( h = 0.2 \text{ m} \) (height) and \( b = 0.1 \text{ m} \) (wide cross section).

\[
Y_{\text{max}} = \frac{Pl^3}{48EI}
\]  

The comparison between the values of the maximum displacement of the numerical model made of glass ceramic and analytical results are presented in Table 3. These results showed that the numerical model proved compatible bringing good representation of the real test.

Subsequently, when compared the \( Y_{\text{max}} \) between numerical models. First, the maximum displacement at mid-span was 1.69E-04 m in the model made by composite model glass ceramic/steel with the arrangement with two steel bars, showed in Figure 3. In the model with the arrangement with three steel bars, Figure 4, the maximum displacement was of 1.75E-04 m. The decrease in displacement indicates an increase in mechanical stiffness of the
composite, potentiating the resistance of the beam, which brings good prospects for use of glass ceramic/steel composite in various structures.

Table 3. comparison between $Y_{\text{max}}$ values obtained from the numerical model and displacement calculated by Euler Bernoulli analytical equation (equation 1).

<table>
<thead>
<tr>
<th>Model</th>
<th>$Y_{\text{max}}$ (m)</th>
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</thead>
<tbody>
<tr>
<td>Euler Bernoulli (analytical)</td>
<td>1.92E-04</td>
</tr>
<tr>
<td>Glass ceramic (numeric)</td>
<td>1.92E-04</td>
</tr>
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</table>

Using Equation 1, it could be calculated the critical load ($P_{\text{cr}}$) to be applied to nucleation cracks in the numerical model made of glass ceramic. In this expression, $l$ is the distance between supports, $b$ is wide cross section of the beam and $h$ is its height.

$$\sigma_{\text{cr}} = \frac{3P_{\text{cr}}}{2bh^2}$$

The numerical distribution of strain fields of cracking is shown in Figure 8. For analysis, we chose a cross section of mid-span at the end of the test. You can check that the lower central region is the critical portion of the bar, demonstrating the fragility of the material tensile strength.

![Figure 8. Numerical distribution of equivalent cracking strain.](image)

5. OVERALL CONCLUSIONS

This paper presented a numerical analysis of the glass ceramic material (Zerodur®) and the glass ceramic/steel composite by finite element method (FEM). The mechanical behaviour was evaluated numerically by simulating of bi supported beam subjected to bending testing.

The results show good numerical representation of the test compared with the analytical model for displacement of beams. It can be seen improvement in the mechanical performance of this glass ceramic when structured with
carbon steel bars. However, it should be establish an appropriate region for inclusion of bars and a streamlined
process to join materials.

6. REFERENCES


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