EVALUATION OF THE MECHANICAL BEHAVIOR OF A CERAMIC GLASS COMPOSITE THROUGH 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 trade name given to an inorganic material with low thermal expansion, widely used in equipment subjected to large temperature variations, where 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 behavior 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 behavior 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 behavior is 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 mechanic means 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 (Calister, 2002). 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 nonmetallic 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 behavior 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 (Finite Element Method) of composites with the matrix phase as Zerodur® and dispersed phase as small longitudinal bars of Steel. This arrangement aims to improve the mechanical behavior of Zerodur® when subjected to the numerical flexural test. The mechanical stiffness of the material was evaluated according to displacement values.

In the second half will be presented a model according to the crack strain damage criterion of a structure with 100% Zerodur®. 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 ™ (2010).

2. ZERODUR®

In 1968, Schott Glass Technologies Inc.© developed the Zerodur®. 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 machinable 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, high precision, large mirrors for astronomical telescopes and standards for technology precision measurement, Fig 1. However, this glass ceramic has a low modulus of elasticity, consequently, low structural rigidity, and a typical brittle behavior of ceramics, limiting its use.

Figure 1. Measurement Standards made from Zerodur®.

Production of Zerodur® 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 (Hartmann et al., 2008). During this treatment centers 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 (Dohring et al., 2005):

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

Basically, this glass ceramic is formed by oxides (Li_2O, SiO_2, Al_2O_3), 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 (Mirkarimi et al., 2000).

It also has good processability, in other words, it is easy to handle during manufacturing despite having a temperature range of synthesis that goes from 700 to 1000 ° C (Berezhinsky et al., 2004).

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 the Zerodur® a material with low thermal expansion. In certain ranges of temperature coefficient of thermal expansion may be approximately zero or even slightly negative, depending on the process used ceramization (Schmitz et al., 2002).

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 11nm 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 (Soufli et al., 2007).

When referring to the transparency of 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 improve the percentage of the two phases to establish more precisely the desired degree of purity (Mirkarimi et al., 2001).

3. MATERIALS AND METHODS

3.1. Bending Test of Three Points

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 center of the bar, as Fig. 2.

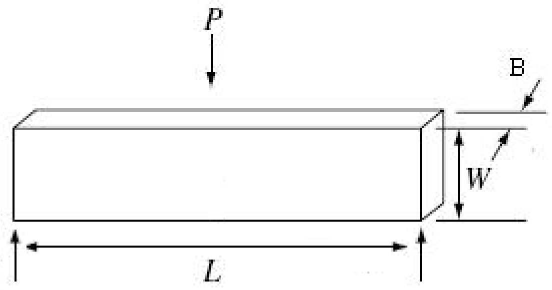

Figure 2. Bending Test of Three Points

To define the dimensions of the specimens of the bending test was used as the basis of the technical references ASTM E399 (1996). The relations defined in this standard are illustrated in Fig. (2), where *L* is the distance between supports, *W* is the height, *B* is width and *P* is the applied load.

In this study, to be represented numerically the bending test of the composite analyzed. This composite has as matrix phase the Zerodur® and as the dispersed phase carbon steel bars, arranged as shown in Figs. 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 behavior of a beam of the same dimensions made with only the glass ceramic material (Fig. 5).

It is also expected that the metal bars have a greater contribution to resist the tensile stresses from the bending of the beam (Miranda, 2010).

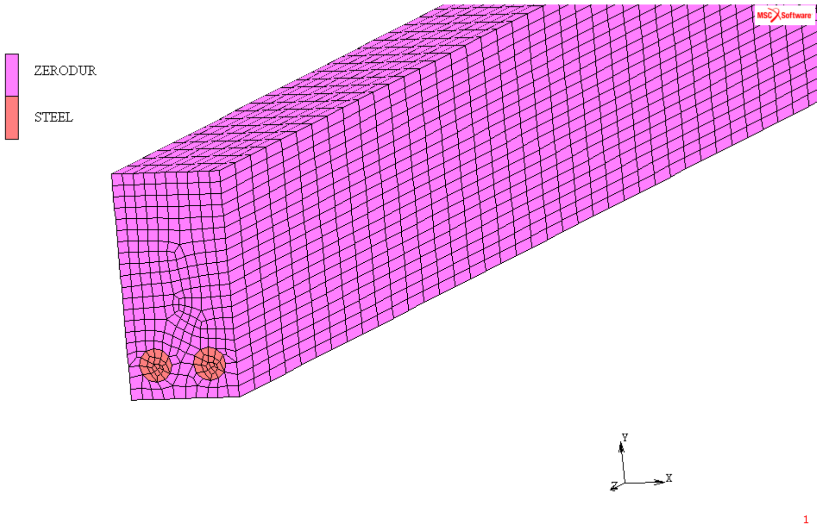

Figure 3. Zerodur®/Steel Composite – arrangement with two bars

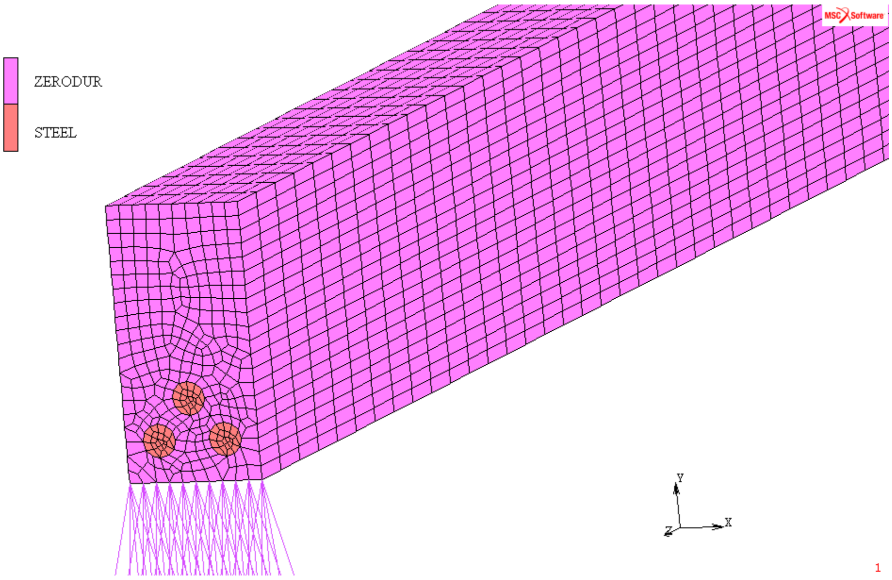

Figure 4. Zerodur®/Steel Composite – arrangement with three bars

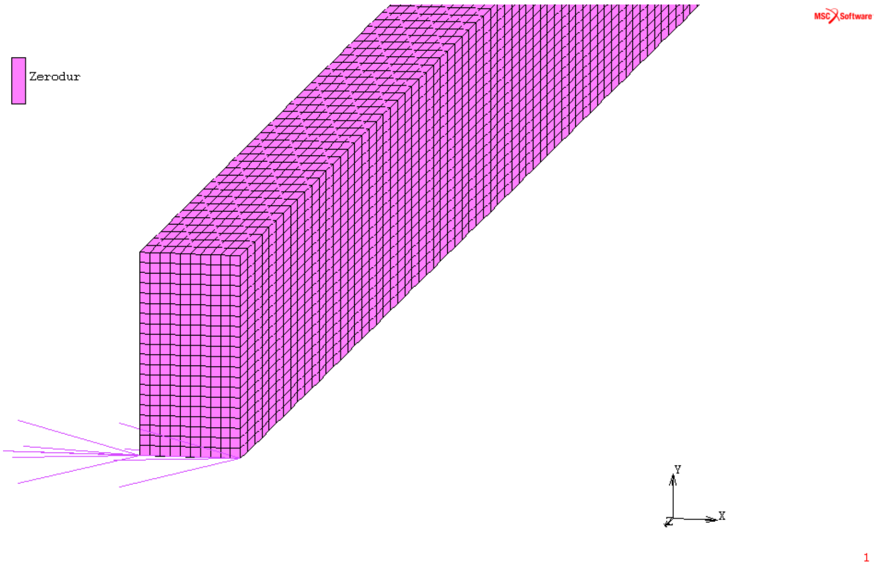

Figure 5. 100% Zerodur®

We used finite element numerical models to simulate the mechanical behavior in bending. Initially, it was simulated the behavior of a sample 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 have symmetry.

Given the parameter Y_{max} for different configurations of beams evaluated the mechanical stiffness of the joint.

3.2. Crack strain

To simulate the behavior of Zerodur® during the bending test in three points was incorporated into the numerical model some mechanisms of fracture processes analysis through a constitutive relation based on classical models of continuum mechanics. These mechanisms are known as crack strain and are represented by curve of uniaxial tension versus strain (Fig. 6).

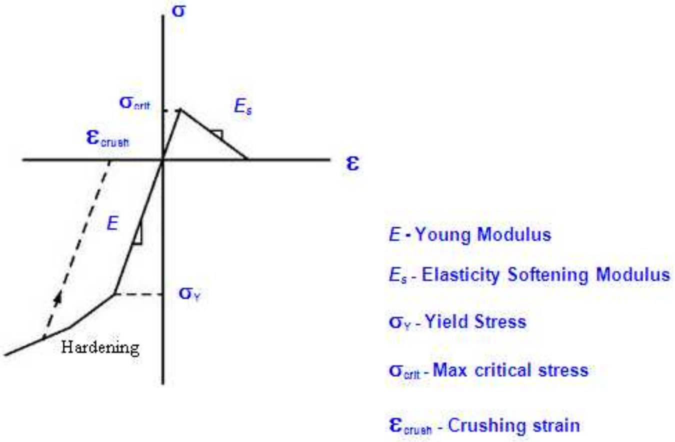

Figure 6. Uniaxial diagram of stress versus for the crack strain model (Adapted from Dias, 2010; Marc, 2010).

For tensile stresses, the crack strain model allows an elastic behavior until the breaking point (σ_{cr}). Reaching this limit, it is assumed the material is cracking in the direction normal to the maximum principal stress (Rankine theory). Initially the model behaves as an isotropic material. After the formation of first crack, the model is replaced by an orthotropic behavior. 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 behavior 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 (Oller, 2001).

The Zerodur® presents a behavior 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 (Trent, 1984).

Input parameters for the model are presented in Tab. 1. By successive numerical analysis for calibration of the module of softening, it was found that the same can be estimated as one hundredth of the value of Elasticity modulus of Zerodur® (Pereira et. al., 2007). The calibration method consists in analysis of the tensile stress in cracked points. The softening modulus prevents that the tensile stress tends rapidly to zero after the maximum normal stress exceeded the yield strength. This parameter can be determined from the material characteristics and geometry of the mesh used.

Table 1. E, E_s, σ_{cr}, ε_{crush} parameters

E	E_s	σ_{cr}	ε_{crush}
91 GPa	9,1 GPa	98 MPa	1000

By Eq. 1, we calculated the F_{cr} (critical load) to be applied to nucleation of cracks.

$$F_{cr} = \frac{2\sigma_{cr} b h^2}{3l} \qquad (1)$$

Where, l is the distance between supports, b is wide cross section of the bar and h is height.
O valor da carga crítica estabelece a força necessária para nucleação de trincas com conseqüente colapso da viga. Para efeito de projeto estrutural deve-se levar em consideração este valor diminuído de um fator de projeto, uma vez que teremos uma fratura típica de materiais frágeis.

4. RESULTS AND DISCUSSIONS

To model the beams subjected to bending, restricted to the displacement at the supports in the directions x, y and z. We applied a total load of 500 N at mid-span of samples. The Fig. 7 shows all boundary conditions of the numeric test.

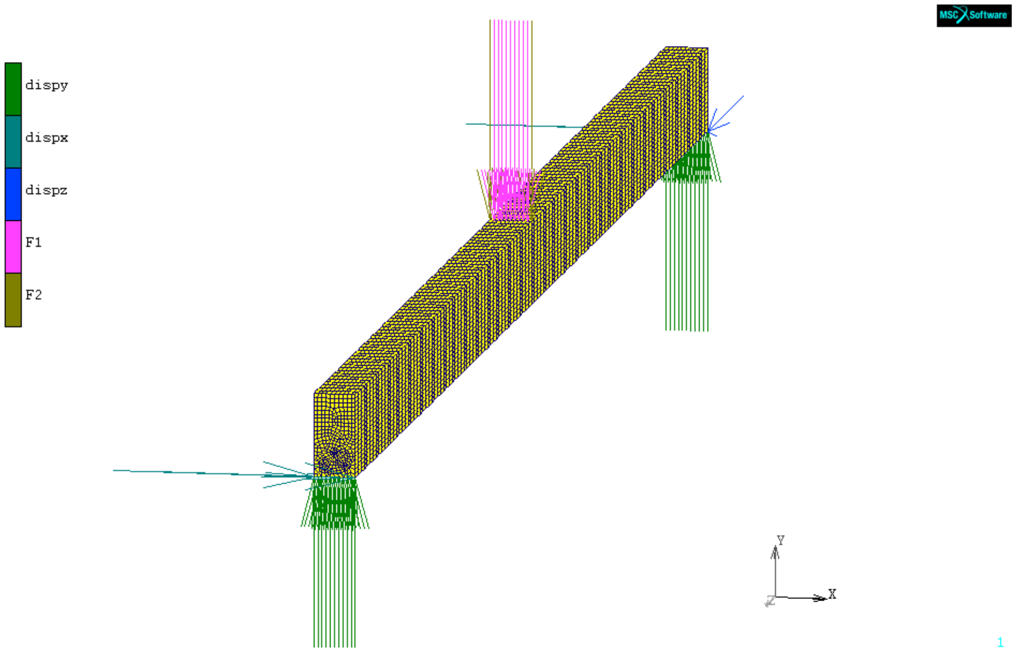

Figure 7. Boundary conditions of numeric test.

According to the referential system *dispy* is support in direction *Y*, *dispx* is restriction in direction *X* and *dispz* is restriction in direction *Z*. *F1* and *F2* are the loads.

The result of the numerical model of the bar 100% Zerodur 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, Eq. 2. Y_{max} is the maximum displacement of the bar that occurs at mid-span, F is the applied load, l is the distance between supports, E is the Elasticity modulus of the material and I the moment of inertia of cross section.

Adopted the following values: $l = 4.8$ m, $h = 0.2$ m and $b = 0.1$ m.

$$Y_{máx} = \frac{Fl^3}{48EI} \qquad \text{Euller Bernoulli} \qquad (2)$$

Table 2 shows the mechanical properties adopted for the ceramic glass and steel.

Table 2. Mechanical properties of constituent materials (Matweb, 2011)

Material	Elasticity modulus (E)	Poisson Coefficient (ν)
Zerodur®	91 GPa	0,24
Aço	210 GPa	0,300

The comparison between the values of displacement of the numerical model of the bar 100% Zerodur and analytical, are presented in Table 3. The numerical results proved compatible bringing good representation of the real test. This type of analysis is done to measure the adherence of the numerical model to the actual test (mesh calibration).

Table 3. Displacement values (Y_{max}) obtained from the numerical model and displacement calculated by Euller Bernoulli analytical equation.

Model	Y_{max} (m)
Euller Bernoulli (analytical)	1,92E-04
100% Zerodur® (numeric)	1,92E-04

Subsequently, we compared the Y_{max} of the numerical model with 100% Zerodur® as Y_{max} composites Zerodur®/Steel presented in different settings. In the arrangement with two steel bars, we obtained a displacement at mid-span of 1.69E-04 m. The arrangement with three steel bars had displacement 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 Zerodur®/Steel composite in various structures.

The numerical distribution of deformation fields of cracking is shown in Fig (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. The scale of colors represents the crack strain level (dimensionless). The crack is going to start in the lower portion of the beam.

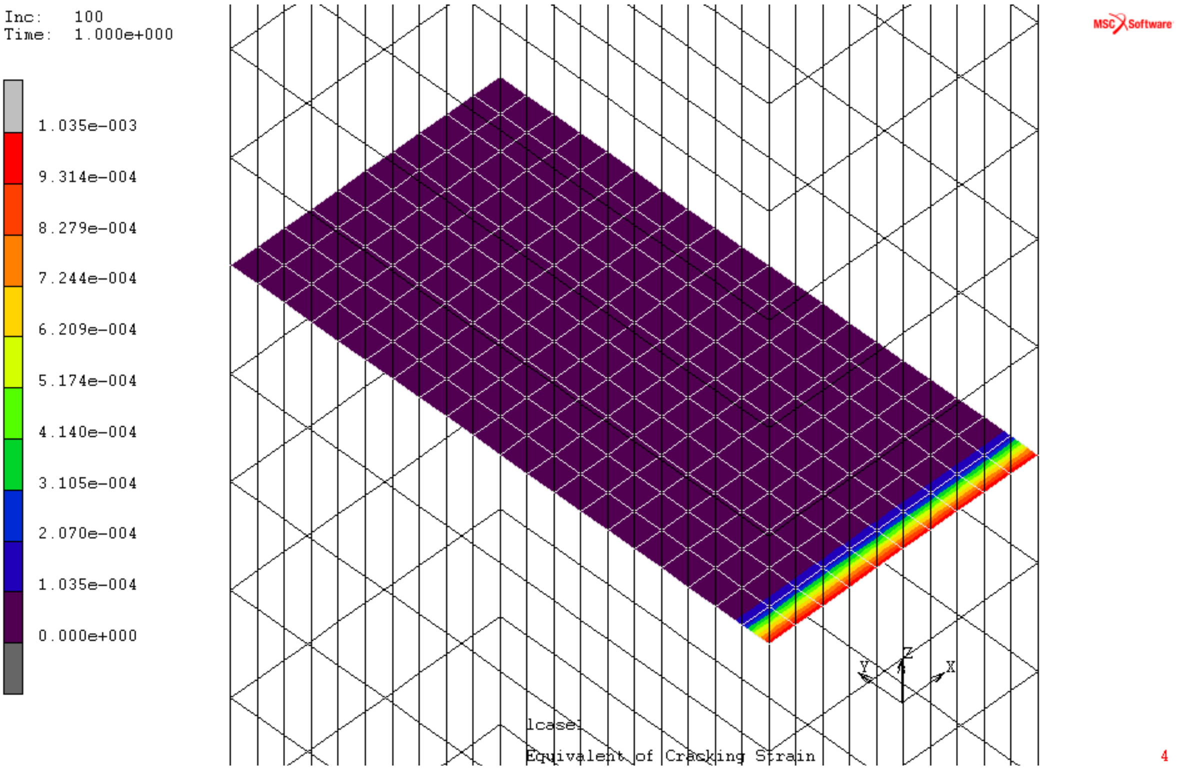

Figure 8. Distribution of strain fields by the cracking bending in three points.

5. CONCLUSIONS

This paper presented a numerical analysis of the material Zerodur® glass ceramic and the Zerodur®/Steel composite by finite element method (*FEM*). The mechanical behavior was evaluated numerically by simulating of bi supported beam subjected to bending. The paper represents significant gains for materials engineering. Zerodur® is the material with excellent mechanical properties, but because of its fragility is still not widespread. The Zerodur®/Steel composite has good prospects of application as an alternative material to be used on the basis of measurement equipment of high accuracy. The composite has stability even with temperature variation and rigidity to support the loading.

The numerical analysis presented is simple, but it has high relevance in the stiffness analysis of these beams.

The bending test on three presents peculiarities from the viewpoint of fracture mechanics and is suitable for assessing the behavior of brittle materials. In this work, we chose to use this type of test over the need to explore solutions that contribute to increasing the mechanical strength of Zerodur ® when subjected to bending. The proposal is to increase the stiffness of the beams by adding steel bars as reinforcement. In the initial phase of research emerged a few options for strengthening such as carbon fiber, carbon steel and fiberglass.

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 Zerodur® 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.

The choice of using carbon steel as reinforcement was motivated by analysis of the compatibility matrix and fiber phases (Zerodur®/Steel) in relation to aspects of the proposed structural composite manufacturing. At present we are examining ways to manufacture the composite Zerodur ® / Steel. It is possible by conventional smelt methods. This method involves high temperatures and could result in structural transformations of steel. Another possibility would be to use manufacturing processes by means of high precision machining. These discussions are proposed scope for future work. We are going to study the stress in the interface between Zerodur®/Steel analyzing the effect of friction between the phases.

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