Finite Element Analysis to investigate the significance of functional gradients in dental restorations

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INTRODUCTION

Many of our modern technologies require materials with better mechanical, thermal, electrical and optical properties that cannot be met by the conventional metal alloys, ceramics, and polymeric materials. This is especially true for materials that are needed for aerospace, underwater, and transportation applications.
For example, aircraft engineers are constantly in the search of materials that is lightweight yet strong, stiff and not easily corroded. Such materials that have different combinations of characteristic have been made possible by the development of functionally graded materials (FGM). The purpose of these structures is to provide a smooth transition between materials, which are otherwise incompatible because of their mechanical or chemical properties.

Functional gradients refer to the grading of a specimen into different layers either horizontal or vertically, each layers having a different Young's modulus (E).

The human teeth acts like a mechanical device whenever we eat our food. Like all mechanical devices, the teeth can fail if subjected to a great deal of stress or due to fatigue. Traditionally, the material used in dental restoration has a constant elastic modulus. However, it has been found that the human teeth is not homogeneous in nature thus using a homogeneous material when replacing lost tooth will result in stress concentration to arise between the teeth bone interface. This is because the teeth have a large E of about 84.1 GPa for the enamel while the tooth-bone interface has a small E of 1.18 GPa (fig. 1). As such the replaced structure will be prone to failure due to the presence of stress concentration.

Therefore, the objective of this report is to investigate, using finite element analysis, how different horizontal functional grading configurations of a specimen will affect its properties and behavior under loading and the effectiveness of a FGM in helping to reduce the stress concentration that exist in the tooth – bone interface. The research does not cover on the investigation of a human dental structure under loading, but rather, using a cantilever model as a first step to determine if FGM material is effective in reducing stress concentration and the best suitable functional grading configuration that can be applied in dental restoration. The research also did not attempt to investigate how vertical grading or combination of both will affect a specimen's properties.

MATERIALS AND METHODS

The investigation was carried out in ANSYS ver 5.5 using layered solid element type (SOLID 46). The cantilever model was formed using 100 SOLID46 elements. The cantilever that was graded horizontally has dimensions of 1000 x 20 x 20mm (fig. 2). The Young's modulus of the graded cantilever was allowed to vary between 10 GPa and 20 GPa. 2 methods of horizontal grading were used: 1. The outer layers have material with the highest Young's modulus and 2. The outer layers have material with the lowest Young's modulus.

1. The model is graded in steps of 10 GPa. That is, each adjacent layer has a Young's modulus of 10 GPa difference. In this case, the model consisted of four layers with the outer most layers of the cantilever having a Young's modulus of 20 GPa and the 2 inner layer having a material property of 10 GPa. Each of the layers has the same cross-sectional area.

2. A bending moment of 80 Nm was applied to the free end of the cantilever. The deflection, stress and strain results were obtained from ANSYS and recorded.

3. The above steps 1 – 2 were repeated for grading step of 5, 2.5, 2, 1, and 0.5 GPa.

4. The whole investigation (steps 1 – 3) above was repeated with the exception to step 1 in that instead of the outer most layers of the cantilever having the highest Young's modulus of 20 GPa, it is assigned the lowest Young's modulus which is 10 GPa. That is, the layer configuration was reversed.

RESULTS AND DISCUSSION

The deflection for lower E material on the outer layers vary from 242.356mm to 266.72mm, having a range of 24.364mm (fig. 3), and the deflection gets lesser as the step size decreases (i.e. having more layers). The stress in the x-direction also decreases as the step size decreases, varying between 48.462 MPa to 60 MPa, with a range of 4.871 MPa (fig. 4). The strain in the x-direction also follows the same trend varying between 0.004846 to 0.005333, having a range of 0.000487 (fig. 5).

The deflection for higher E material on the outer layers vary between 160.032mm to 170.304mm, having a range of 10.272mm (fig. 6), and the deflection increases slightly as the step size decreases (i.e. having more layers). The stress in the x-direction also increases as the step size decreases, varying between 64 MPa to 68.108 MPa, with a range of 4.108 MPa (fig. 7). The strain in the x-direction also follows the same trend varying between 0.0032 to 0.003405, having a range of 0.000205 (fig. 8).

It was noted that for both configurations, the deflection, stress and strain graphs showed signed of leveling off at a certain point if the layers were to be further increase. Meaning that it will no longer be useful to further increase the layers since it will have little or no effect on the helping to reduce the stress discontinuity. The deflection of the cantilever due to the 80 Nm bending moment at the end of the beam for the higher E material on the outer layers is very much lesser (about 70mm or 30% lesser) than the reversed configuration. Thus, the strain in x-direction experienced is also 30% lesser (since strain is defined as deformation per unit length). The stress in the x-direction conversely (since E=ó / å) increases as step size decreases, since the strain in x-direction increases.

From figures 9, 10 and 11, it can be seen that as the step size decreases, the graph of layer step against stress X (MPa) is becoming more like a straight line. This means that the stress distribution is becoming more similar to that of a homogeneous material. The large stress discontinuity occurring (if there were only 4 layers) was greatly reduced as the step size decreases, and this is particularly useful since the tooth bone interface is of such nature (fig. 1).

From figures 12, 13 and 14, it was observed that having lower E material on the outer layer have stress discontinuity moving inwards. This is because the strain experienced by the higher E material is lesser since it is nearer to the neutral axis and the lower E material experienced more strain as it is in the outer side of the cantilever. The stress in the x-direction (fig. 14) seems to be leveling off at a particular as the step size decreases.

CONCLUSION

The tooth is a very complex and is non-homogeneous in its E properties. The tooth – bone interface has caused much stress concentration to arise due to the great difference in their material properties. However, it has been shown above that, FGM is capable of and helpful (especially when the grading step is small) in reducing the stress concentration that may arise between the tooth – bone interface in dental restoration.

The above investigation also suggest that the configuration that have the higher E material at the outer layers will be the best suited for grading the material to be used as a tooth replacement. This is because the stress discontinuity that arises is gradually being modified to a linear stress across the material as the step size decreases.

Since this research only deals with horizontal grading, it is suggested that future investigations maybe to deal with the significance of vertical grading or a combination of both or to use FEM to simulate the tooth – bone interface and using one or a combination of the grading methods to determine the most suitable material for tooth replacement.

ACKNOWLEDGEMENTS

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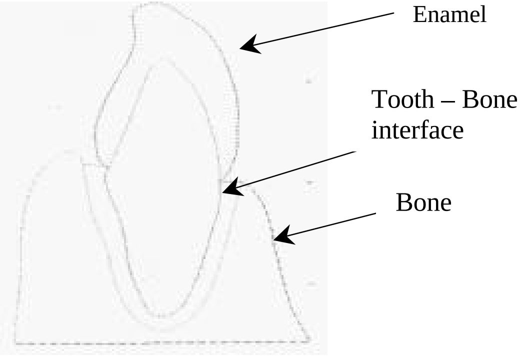

Figure 1: Tooth structure

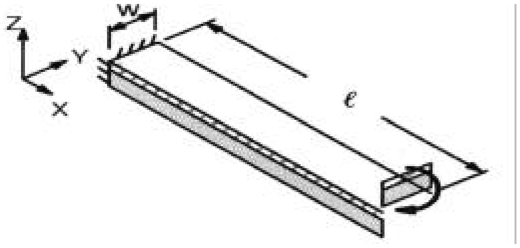

Figure 2: The cantilever model

a.) **Low E material at outer layers**

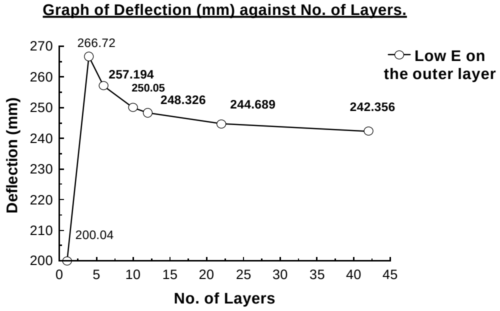

Figure 3: Deflection against No. of layers

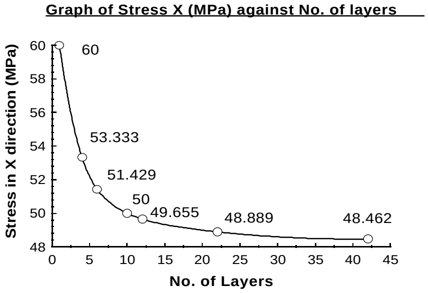

Figure 4: Stress X against No. of layers

b.) **High E material at outer layers**

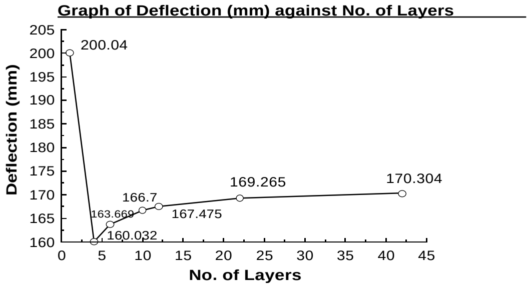

Figure 6: Deflection against No. of layers

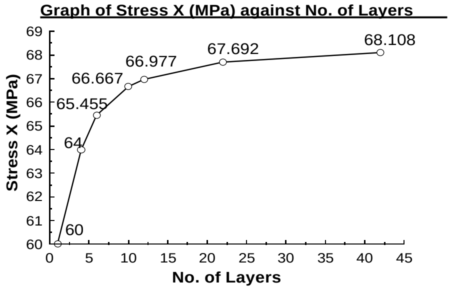

Figure 7: Stress X against No. of layers

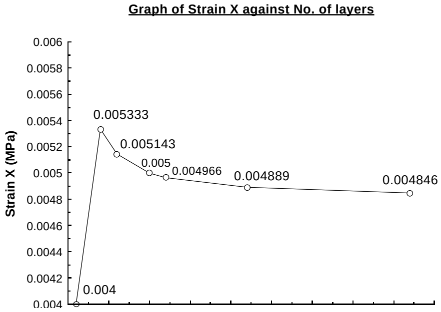

Figure 5: Strain against No. of layers

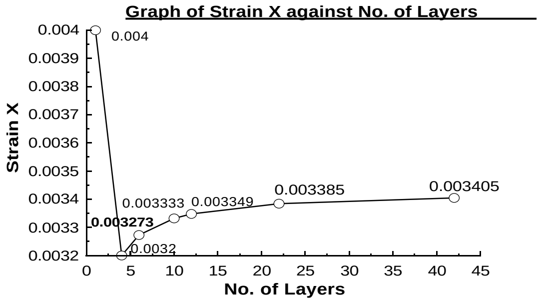

Figure 8: Strain against No. of layers

Graph of layer step against stress X (MPa)

The below graphs were obtained for an applied bending moment of 80 Nm at the end of the cantilever. Also, the graphs were plotted for the tensile region only, since the modeled cantilever is symmetrical.

a.) High E material at outer layers

b.) Low E material at outer layers

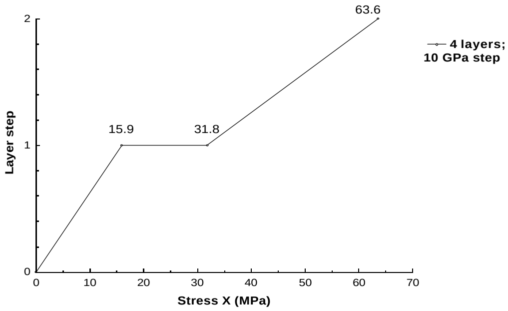

Figure 9: Model graded in 10 GPa steps

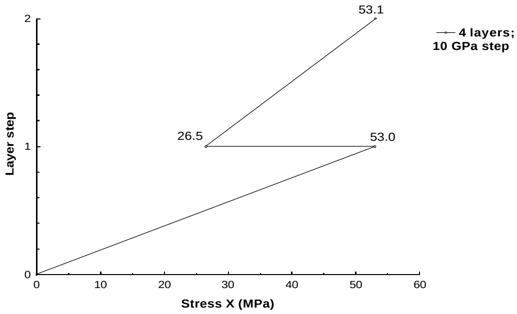

Figure 12: Model graded in 10 GPa steps

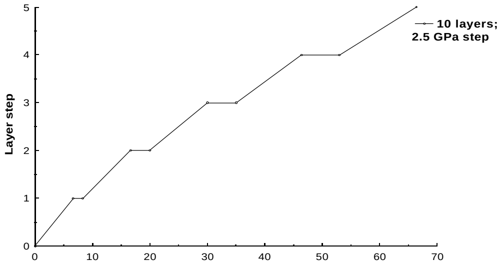

Figure 10: Model graded in 2.5 GPa steps

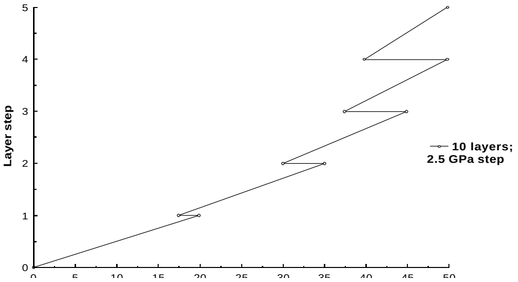

Figure 13: Model graded in 2.5 GPa steps

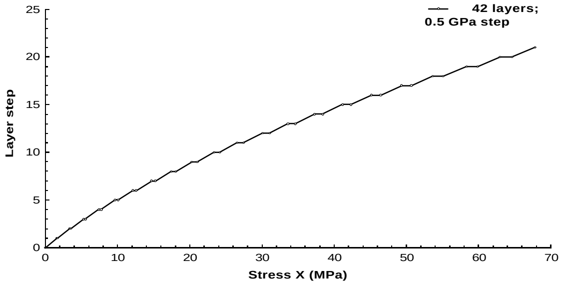

Figure 11: Model graded in 0.5 GPa steps

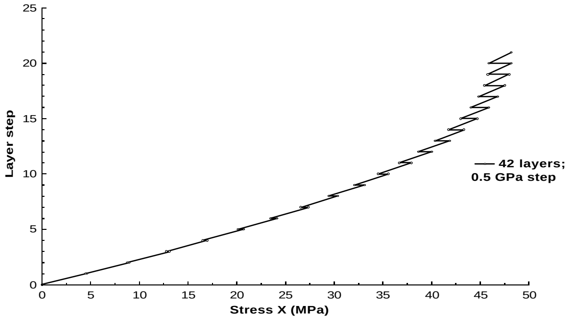

Figure 14: Model graded in 0.5 GPa steps