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A finite element study on the fracture initiation at the zirconia/ veneer interface: An application in dental materials

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Zirconia/ veneer bi-layered components are extensively used in dental restoration technology to improve resistance of tooth's surface from decay. The direction of the fracture propagation at the interface of zirconia and veneer is investigated in this paper. Finite element analysis is performed on a bi-material four point bend specimen in different geometries, and the fracture initiation angle is obtained using maximum tangential stress (MTS) criterion. The effect of specimen geometry on the fracture initiation angle is discussed. Because an interface crack may propagate through interface or kink into one of the materials, some comments are given to determine under which condition "interface de-bounding" will be happened.

1. Introduction

Restored teeth undergo complex loading conditions during their service life (Kotousov et al., 2011; Chai et al., 2014; Kosyfaki & Swain 2014). Veneers which are made from dental porcelain or composite, are widely used in dentistry to protect tooth's surface from decay. In dental prostheses, the zirconia-based bi-material restorations are widely employed to reform the damaged parts of teeth. That is because the veneering porcelain sintered on zirconia (zirconia/ veneer interface) has a high strength (Fischer et al., 2008; Gostemeyer et al., 2010; Mosharraf et al., 2011; Kim et al., 2011).

In a restored tooth, under service condition, cracks may develop at the interface of zirconia and veneer as a result of the external mechanical loading. Thus, the study of fracture propagation condition at the interface of the zirconia and veneer is an important issue in the field of dentistry. Generally, the fracture in either homogeneous or bi-material media has widely been investigated by many researchers so far (Ayatollahi & Aliha 2011; Aliha & Ayatollahi 2008, 2012; Arabi et al., 2013; Ayatollahi et al.,

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2010a,b, 2011a; Ayatollahi & Mirsayar, 2011; Mirsayar, 2013, 2014a, b; Mirsayar & Samaei, 2013, 2014; Mirsayar et al., 2014; Mirsayar & Park 2015). Previously, the researchers have mostly focused on the enhancement of the bond strength rather than the fracture mechanics aspect of the zirconia/veneer interfaces (Mosharraf et al., 2011; Kim et al., 2011). However, in the past few years, researchers were interested in interfacial fracture resistance of the all-ceramic restorations (Kotousov et al., 2011; Gostemeyer et al., 2012). Several fracture test specimens are employed by the researchers in the past to investigate the interfacial fracture resistance of the specimens containing a bi-material and simple cracks (Ayatollahi et al., 2013; Charalambides et al., 1989; Yuuki & Xu, 1992; Mirsayar 2014c, 2015). Among them, the bi-material four-point bend specimen developed by Charalambides et al. (1989) has widely been accepted by the researchers. They have conducted experiments on the bi-material four-point bend specimens made from Aluminum and PMMA.

There are several fracture criteria to investigate the fracture initiation conditions at the interfacial crack tip. The well-known fracture criteria are: the maximum tangential stress (MTS) (Yuuki & Xu, 1992), $K_{II} = 0$ (Cotterel & Rice, 1980), and energy release rate (G) (He & Hutchinson, 1989). However, these criteria are modified recently to provide more accurate estimation of the test results depending on different specimen geometries and boundary conditions. For instance, Mirsayar (2014a) showed that to achieve an accurate estimation of the interfacial fracture resistance, the first non-singular stress term of the elastic stress field (called T-stress) should also be considered when employing the MTS criterion.

In this paper, the fracture initiation condition at the interface of the zirconia and veneer is studied using bi-material four-point bend specimen suggested by Charalambides et al. (1989). The finite element software ABAQUS is employed to simulate the specimen in different geometries. For each case, the direction of the fracture initiation is obtained using the MTS criterion. Finally, some comments are given about the possibility of the crack kinking out of the interface as well as crack propagation through the interface.

2. Problem Statement

Fig. 1 shows the general configuration of the bi-material four-point bend specimen made from zirconia and veneer. The specimen has a central notch through the thickness of the veneer (top layer) which meets the middle of the symmetrical interface crack. The specimen is simulated in different thickness layer ratio (h_1/h_2 = 0.5, 1, 2) and different normalized crack sizes (a/c = 0.1, 0.3). The elastic properties of the veneer (IPS e.max Ceram) and zirconia (Lava Zirconia) are $E_v = 70GPa$, $\nu_v = 0.27$ and $E_z = 210GPa$, $\nu_z = 0.31$, respectively, where E_i is the elastic modulus and ν_i is the Poisson's ratio of each material ($i \equiv$ v, z) (Wang et al., 2014).

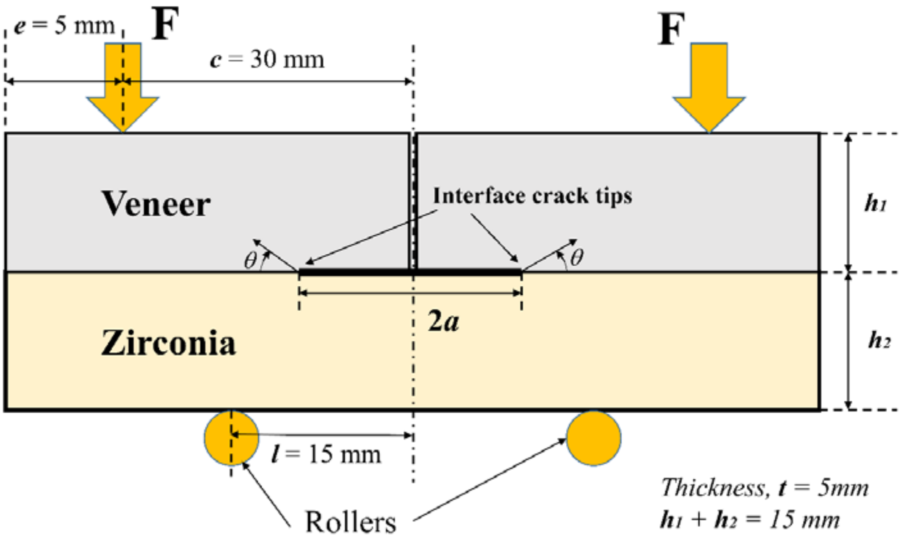

Fig. 1. General configuration of the bi-material four point bend specimen

When the specimen is loaded, the interfacial crack may propagate through the interface or may kink into one of the materials depending on the strength of the interface. Based on the experimental observation given in the literature (see for instance, Wang et al., 2014) the zirconia / veneer bonded joints can be considered as “strong interfaces”, and hence, the interface crack usually kinks into one of the materials instead of growing through the interface. However, the mechanism of the crack propagation at the interface is affected by the strength of the interface as well as each material.

3. Results and Discussion

3.1 Finite element simulation of the specimen

Fig. 2 shows a typical finite element mesh generated using eight node plane strain elements along with an expanded view of the crack tip singular elements (for h_1/ h_2 = 1 and a/ c = 0.1). The specimen is simulated in different geometries to obtain the effect of geometry on the crack initiation condition at the interface crack tip.

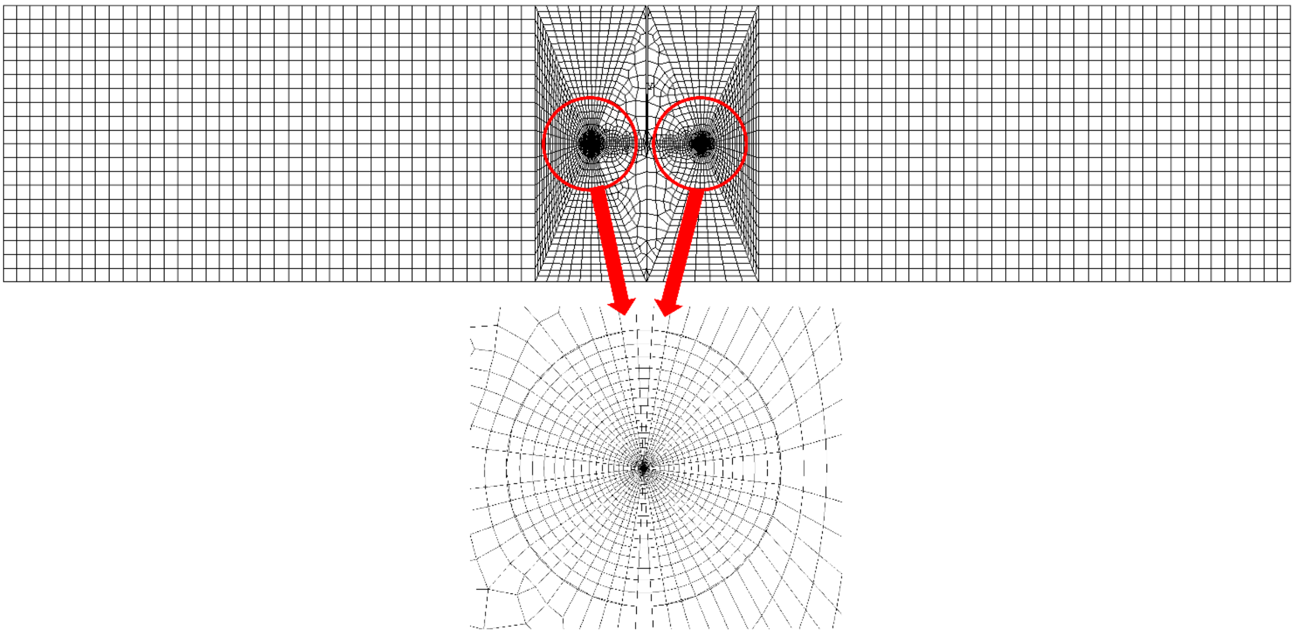

Fig. 2. Typical finite element mesh pattern of the bi-material four-point bend specimen

3.2 MTS criterion for initiation at the crack tip

Based on the MTS criterion, for brittle materials, the crack propagates at the critical distance of r_c from the crack tip in direction where the tangential stress, $\sigma_{\theta\theta}$, reaches its ultimate strength. This criterion was developed originally for problem of a crack which exists in a homogeneous media (Erdogan & Sih, 1963) and since then has been successfully used for predicting the mixed mode brittle fracture of various brittle and homogenous materials (such as Williams & Ewing, 1972; Awaji & Sato, 1978; Shetty et al., 1987, Maccagno & Knott 1989; Suresh et al., 1990; He et al., 1990; Smith et al., 2001; Aliha & Ayatollahi, 2008, 2011, 2014; Ayatollahi et al., 2006, 2008, 2011b; Aliha et al., 2008, 2012; Ayatollahi & Aliha 2008; Saghafi et al., 2010). However, by the same concept, the MTS criterion could be applied for the interface cracks by controlling the ultimate strength of both materials (at their corresponding critical distances, $r_c^{(i)}$) as well as the strength of the interface. For “strong interfaces”, the MTS criterion could be expressed as follows;

$$\begin{cases} \left(\dfrac{\partial \sigma_{\theta\theta}^{(i)}}{\partial \theta} \right)_{r_c^{(i)}, \theta_0^{(i)}} = 0 \\ \left(\dfrac{\partial^2 \sigma_{\theta\theta}^{(i)}}{\partial \theta^2} \right)_{r_c^{(i)}, \theta_0^{(i)}} < 0 \end{cases}, \tag{1}$$

where the critical distance, $r_c^{(m)}$, is defined as;

$$r_c^{(i)} = \frac{1}{2\pi} \left(\frac{K_{IC}^{(i)}}{\sigma_C^{(i)}} \right)^2, \tag{2}$$

where $K_{IC}^{(i)}$ and $\sigma_C^{(i)}$ are fracture toughness and ultimate tensile stress of each material, respectively. The elastic tangential stress field, $\sigma_{\theta\theta}$, is expressed in the form of a series of expansion with infinite terms containing singular (first and second terms) and nonsingular terms, as follows;

$$\sigma_{\theta\theta}^{(i)} = \frac{K_1}{\sqrt{2\pi r}} f_{\theta\theta,1}^{(i)} + \frac{K_2}{\sqrt{2\pi r}} f_{\theta\theta,2}^{(i)} + T^{(i)} + (H.O.T), \tag{3}$$

where, K_1 and K_2 are the stress intensity factors corresponding to opening and sliding mode, respectively. The parameter T, called T-stress, corresponds to the first non-singular stress term (more details about this term can be found in Mirsayar (2014a)). Although, in vicinity of the crack tip, the singular terms can reasonably predict the tangential stress field, it is recently shown by Mirsayar (2014a) that the first non-singular term sometimes plays an important role in prediction of the tangential stress distribution as well as the fracture initiation conditions around the crack tip. However, in this paper, the fracture initiation direction is predicted by the tangential stress which is directly obtained through the finite element analysis.

3.3 *Finite element results*

Fig. 3 shows the distribution of the normalized tangential stress in different angles, θ, in two normalized crack lengths, a/c = 0.1 and 0.3. All curves are plotted at the radial distance of r = 0.2 *mm* which is within the regular range of the critical distances reported for ceramic materials (Aliha and Ayatollahi, 2012). It is seen that normalized tangential stress increases by increasing h_1/h_2 ratio. That means by increasing the thickness of the veneer (top layer) and decreasing the thickness of the zirconia, the tangential stress at the interfacial crack tip is increased and as a results, the fracture load is decreased.

According to Fig. 3, the tangential stress reaches its maximum value in zirconia part of the specimen. However, depending on the strength of the interface, crack may kink into the zirconia part or propagate through the interface. It should be noted that regardless of the stiffness of the veneer part, the crack will never kink into the zirconia part because the tangential stress at the veneer part reaches its maximum value at the interface. It also could be seen from Fig. 3 that the ratio of $\sigma_{z,\,max} / \sigma_{int}$ is decreased by the increasing h_1/h_2 ratio ($\sigma_{z,\,max}$ and σ_{int} are the maximum value of the normalized tangential stress in zirconia part and at the interface, respectively). That means by increasing the h_1/h_2 ratio, the possibility of crack propagation through the interface is decreased by increasing h_1/h_2 ratio. In other words, the simulation results show that, for a/c = 0.1 and 0.3, the interface strength (under pure tension) must be at least 2.5 times weaker than the tensile strength of the zirconia for having “interface de-bounding" (crack propagation through the interface). Also the comparison between results for a/c = 0.1 and a/c = 0.3 shows that the possibility of the interface de-bounding slightly decreases by increasing the crack length (assuming the same interface strength).

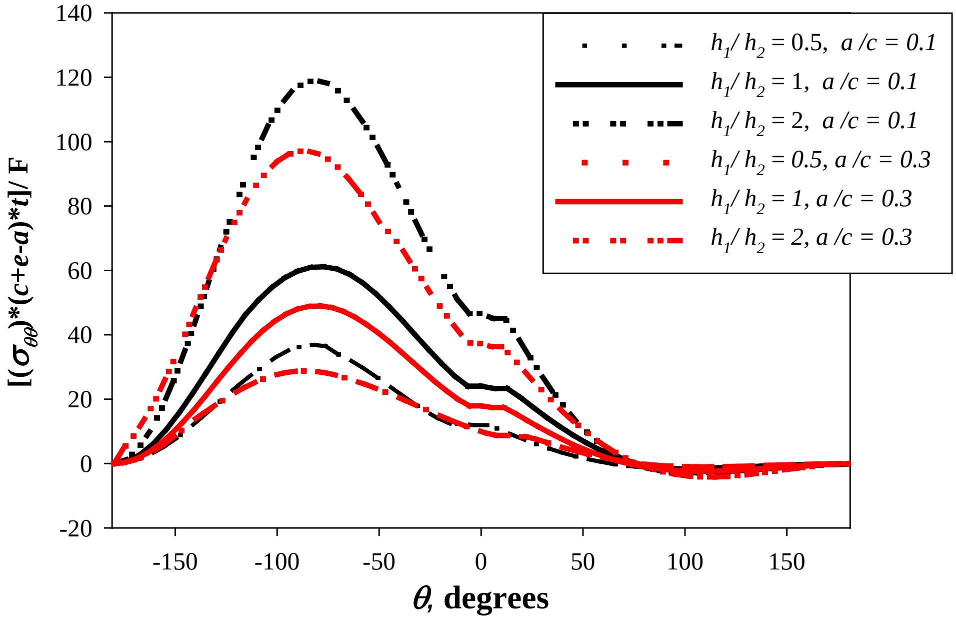

Fig. 3. Distribution of the normalized tangential stress versus tangential direction at $r = r_c = 0.2mm$

Assuming a strong interface in which the crack kinks into the zirconia part, the fracture initiation angle (with respect to the interface) in zirconia part slightly decreases by increasing h_1/h_2 ratio from -78° to -82° and from -80° to -86° for a/c = 0.1 and 0.3, respectively. That means the fracture propagation angle in zirconia part slightly increases by increasing the crack length. It is also observed from Fig. 3 that distribution of the tangential stress field in veneer part approaches zero for $\theta > 80°$. That happens because of the central notch through the thickness of the veneer which provides a stress free area at the veneer part for small values of a/c ratio. The variation of the normalized stress intensity factors versus the h_1/h_2 ratio and for both normalized crack lengths is illustrated in Fig. 4.

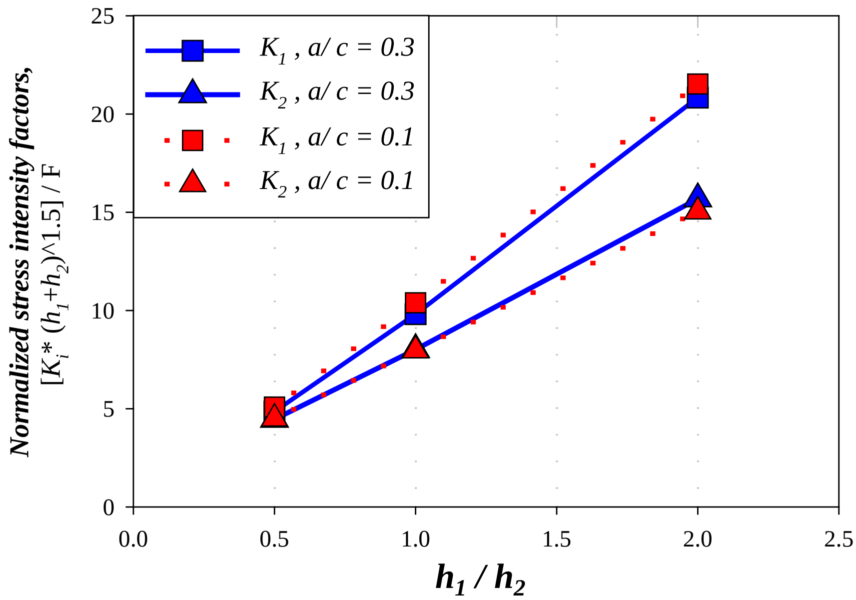

Fig. 4. Variation of the normalized stress intensity factors versus h_1/h_2 ratio

It is shown that the both opening and sliding mode of the fracture are increased by increasing the h_1/ h_2 ratio. However, the opening and sliding stress intensity factors slightly decrease and increase by increasing the normalized crack length, respectively. That means by increasing the normalized crack length, the role of shear stress in the crack initiation condition becomes more important and conversely, the role of normal stresses becomes less important.

4. Conclusion

The bi-material four-point bend specimen, made from zirconia and veneer, is simulated in this paper in different geometries by means of finite element method. The fracture initiation direction is obtained for each cases and the geometry effects are discussed. The condition in which a crack propagates through the interface or kinks into one of the materials is highlighted. Although, the bi-material four-point bend specimen is a well-known fracture test specimen, no recommendation is currently given in literature for using this specimen for zirconia/ veneer interface which are widely used in dental materials. Therefore, the results of this paper could be useful in standardization of the zirconia/ veneer fracture tests.

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