Energy release rate analysis on the interface cracks of enamel-cement-bracket fracture using virtual crack closure technique

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Abstract. This paper presents the energy method to evaluate fracture behavior of enamel-cement-bracket system based on cement thickness. Finite element (FE) model of enamel-cement-bracket was constructed by using ANSYS Parametric Design Language (APDL). Three different thickness were used in this study, 0.05, 0.2, and 0.271 mm which assigned as thin, medium and thick for both enamel-cement and cement bracket interface cracks. Virtual crack closure technique (VCCT) was implemented as a simulation method to calculate energy release rate (ERR). Simulation results were obtained for each thickness are discussed by using Griffith’s energy balance approach. ERR for thin thickness are found to be the lowest compared to medium and thick. Peak value of ERR also showed a significant different between medium and thick thickness. Therefore, weakest bonding occurred at low cement thickness because less load required to produce enough energy to detach the bracket. For medium and thick thickness, both increased rapidly in energy value at about the mid-point of the enamel-cement interface. This behavior occurred because of the increasing in mechanical and surface energy when the cracks are increasing. However, result for thick thickness are higher at mid-point compared to thin thickness. In conclusion, fracture behavior of enamel cracking process for medium most likely the safest to avoid enamel fracture and withstand bracket debonding.

1. Introduction
Bracket debonding occurred during tooth misalignment treatment due to a lot of factors such as incorrect bonding procedures, excessive load exerted from chewing food and unsuitable bracket material used [1]. Therefore, adhesive bonding between bracket and enamel surface should be at optimum state to avoid bracket bonding failure [2]. Two most common debonding type occurred during this failure were at enamel-cement interface and cement-bracket interface [3]. Studying fracture behavior of this two failure condition by using cement thickness as the parameter will lead to a beneficial outcome to improve orthodontist bracket treatment procedure. According to Hajizadeh et al. [4], various factor contributing to bracket debonding based on engineering finding such as tooth surface geometry, bracket base design, location and direction of loading exerted, and adhesive material and geometry. Stress analysis using finite element method (FEM) have been widely used to study bracket debonding. The main purpose of the stress analysis are to recognize the maximum stress region [3]–[5]. However, no fracture mechanics approach to study enamel-cement-bracket system in current research. Using fracture mechanics to study adhesive bonding and debonding was a challenge
because of the stress condition along adhesive joints are quite complex [7]. The complexity of adhesive joints are related to different mechanical properties involve such as young modulus, shear modulus and poison ratio. More challenging factor to study adhesive joint was because of the oscillatory singularity located in the crack tip of the biomaterial interface [8]. Therefore, as suggested by Soderholm. [7], energy method was a better approach to eliminate the oscillatory stress factor to study the interfacial cracks because the result obtained are converged at a better range. Two method widely used to calculate the energy release rate (ERR) which are virtual crack closure technique (VCCT) and $J$ – integral. Both method are comparable and validated with each other as stated in Valvo. [8]. VCCT required lower meshing element to compute 2D and 3D calculation compared to $J$ – integral. This study aims to investigate the fracture behavior of interface cracks to determine the safest thickness range for cement layer of enamel-cement bracket system.

2. Finite element Modelling
Two-dimensional (FE) enamel-cement-bracket model was constructed by using ANSYS Parametric Design Language (APDL). Model geometry are configured according to Elaska et al. [6]. Material properties was set according to Table 1. Shear loading applied on enamel-cement-bracket model to simulate the masticatory process involved during bracket debonding. For this model, soft uniform loading of 10 N load applied on bracket base at bracket top side as shown in Figure 1.

![Figure 1](image-url)

**Figure 1.** (a) Schematic diagram of enamel-cement-bracket model, (b) Loading and boundary condition, (c) Location of interface crack (red line)
In FE modeling, the nodes along enamel outer layer were fix at all direction to make an assumption of enamel as the fix layer. Then, lower area cement, and bracket base layer, fixed at y−direction to avoid cement layer from entering enamel layer. Meshing size 0.1 was used for enamel region near cement layer, bracket base and cement layer. Small meshing size used at the area close to cement layer to avoid meshing error because high stress at that region. The 8 nodes quadrilateral meshing element used to construct the meshing area with meshing size 0.15 is used for the area away from cement layer. For validation, meshing convergence was conducted. This study involved the assumption of homogenous, isotropic, and linear elastic.

| Material     | Manufacturer          | Elastic Modulus | Poisson’s Ratio |
|--------------|-----------------------|-----------------|-----------------|
| Ceramic      | Clarity, 3M Unitek, Monrovia, CA, USA | 380000          | 0.29            |
| Transbond XT | 3M Unitek, Monrovia, CA, USA          | 5000            | 0.30            |
| Enamel       | -                      | 84000           | 0.30            |

Interface fracture concerned in this study are enamel-cement interface and cement-bracket interface. Virtual crack closure technique (VCCT) was used to calculated energy release rate by implementing delamination concept on enamel-cement-bracket model. For this study, a simplified flat cement and bracket base geometry according literature was implemented [6]. The evaluation of ERR by using VCCT according to Valvo. [8] can be expressed as

\[ G_{ERR} = G_{I} + G_{II} + G_{III} \]  

(1)

In this FE formulation, the ERR of interface fracture is evaluated based on

\[ G_{IF} = \lim_{\alpha \to 0} \frac{1}{2S} \int_{0}^{\Delta \alpha} F_{ix} \Delta u_{ix}(\alpha)da + \int_{0}^{\Delta \alpha} F_{iy} \Delta u_{iy}(\alpha)da + \int_{0}^{\Delta \alpha} F_{iz} \Delta u_{iz}(\alpha)da \]  

(2)

The total ERR, \( G_{IF} \) involves the opening of initial combined nodes at crack tip to a new crack tip. \( F_{ix}, F_{iy} \) and \( F_{iz} \) are the forces in \( x \), \( y \) and \( z \) direction. \( \Delta u_{ix}, \Delta u_{iy}, \Delta u_{iz} \) are the displacement in \( x \), \( y \) and \( z \) directions. \( S \) represent the surface area of crack surface. Stated that, the range of cement thickness are from 0.05 to 0.271 mm. Therefore, three cement thickness used in this study are 0.271, 0.2 and 0.05 mm as thick, medium and thin cement layer models. Crack length started from 0.2 until 0.26 were tested for each cement layers. Total ERR for enamel-cement and cement-bracket interface obtained and discussed by using Griffith’s energy balance as stated by Solderholm [7].

3. Simulation result

During bracket debonding, high stress exerted at the edge of enamel labial will caused the present of flaws or cracks to the enamel region [4]. In this study, comparison of thin, medium and thick cement thickness was conducted according to range of cement thickness obtained from previous study. In order to validate the result obtained from VCCT method, the results were compared with ERR obtained from \( J \) - integral method [5]. Validation was conducted for cement thickness 0.2 at enamel-cement interface. As shown in Table 2, percentage error of ERR between VCCT and \( J \) - integral method was less than 1 percent for all crack length. As shown in Figure 2, lowest ERR were obtained when the thin cement thickness applied. This behaviour explained less load needed to cause cement or adhesive failure when thin adhesive layer applied to attach the bracket. This result confirmed the lack of bonding ability of thin cement layer. Therefore, cement thickness applied must be thicker than 0.05mm to avoid bracket debonding due to adhesive failure. Comparing with thick and medium cement thickness, thin adhesive shows a relatively low energy value across all crack length tested and low peak energy value.
Table 2. Comparison of percentage error of ERR for VCCT and J – Integral

| Crack length | ERR (VCCT) | Contour 1 | Contour 2 | Contour 3 | ERR (J – Integral) | % error |
|--------------|------------|-----------|-----------|-----------|--------------------|---------|
| 0.2          | 6.37E-05   | 6.36E-05  | 8.19E-05  | 7.08E-05  | 7.21E-05           | 0.1272  |
| 0.4          | 8.81E-05   | 8.79E-05  | 8.83E-05  | 8.82E-05  | 8.81E-05           | 0.0359  |
| 0.6          | 1.02E-04   | 1.01E-04  | 1.02E-04  | 1.02E-04  | 1.02E-04           | 0.2329  |
| 0.8          | 1.20E-04   | 1.19E-04  | 1.20E-04  | 1.20E-04  | 1.19E-04           | 0.3156  |
| 1            | 1.47E-04   | 1.46E-04  | 1.47E-04  | 1.47E-04  | 1.47E-04           | 0.2268  |
| 1.2          | 1.84E-04   | 1.84E-04  | 1.85E-04  | 1.84E-04  | 1.84E-04           | 0.0886  |
| 1.4          | 2.31E-04   | 2.31E-04  | 2.32E-04  | 2.32E-04  | 2.31E-04           | 0.0706  |
| 1.6          | 2.96E-04   | 2.95E-04  | 2.96E-04  | 2.96E-04  | 2.96E-04           | 0.0720  |
| 1.8          | 3.96E-04   | 3.94E-04  | 3.96E-04  | 3.96E-04  | 3.95E-04           | 0.1079  |
| 2            | 5.73E-04   | 5.71E-04  | 5.73E-04  | 5.73E-04  | 5.72E-04           | 0.1764  |
| 2.2          | 9.55E-04   | 9.51E-04  | 9.55E-04  | 9.55E-04  | 9.53E-04           | 0.1475  |
| 2.4          | 1.99E-03   | 0.001986  | 0.001994  | 0.001994  | 1.99E-03           | 0.0050  |
| 2.6          | 6.27E-03   | 6.29E-03  | 6.31E-03  | 6.31E-03  | 6.30E-03           | 0.4691  |

For medium and thick cement thickness, both having rapid increasing in ERR value at crack length 2.2 mm which is about 2/3 of the cement length. Explaining using Griffith’s energy balance, the rapid increasing of energy value possibly because of the increasing in surface energy as the crack length increased. Due to the increasing of crack length, higher mechanical energy required to withstand the high energy produced from the surface energy.

**Figure 2. ERR for Enamel - Cement**

Therefore, total ERR value should increase with increasing crack length value because total ERR is the summation of mechanical and surface energy occurred at the crack tip. From crack length 0.2 mm to 2.0 mm, medium and thick thickness showing a low energy value. The value of ERR increasing with a relatively small increment at the range of 0.00001 J/mm² to 0.0001 J/mm² for both medium and thick cement thickness. Therefore, it can be concluded that both thick and medium thickness can withstand debonding load because of the increasing in mechanical energy as the crack
increased. However, medium thickness possibly be a better cement thickness to avoid enamel fracture due to high energy produced by thick thickness layer.

Figure 3 shows that low energy release rate value were obtained when thin cement thickness applied. However, increasing in energy value shown at crack length 2 mm. This result showing a different trend for thin cement thickness at cement-bracket interface crack compared to enamel-cement interface crack. This behaviour displayed higher energy when cement-bracket interface fracture occurred compared to enamel-cement interface crack. Therefore, when high possibility of bonding failure to occur when crack are at enamel-cement layer due to less energy required for debonding. For medium and thick thickness, increasing in energy release rate value occurred about half of the cement length. Peak value at crack length 2.6 mm for cement-bracket interface showing a higher value compared to enamel-cement interface for all cement thickness. This behaviour occurred should be because of the shear loading applied near the cement-bracket interface. Therefore, when fracture occurred near cement-bracket interface, bonding failure will easily happen compared to enamel-cement interface.

![Figure 3. ERR for Cement – Bracket](image)

4. Conclusion
As a conclusion, the validation model of to compare VCCT and $J$ – Integral method result in less than 1 percent error. Therefore, validation considered as success. For comparison between cement thicknesses for enamel-cement interface fracture, medium thickness considered as the most suitable cement thickness because the ERRs value obtained are high enough to withstand loading and low enough to avoid enamel fracture. The ERR values obtained for cement-bracket interface crack showing a different trend compared to enamel-cement interface. Increasing in ERR occurred earlier at cement-bracket interface. Therefore, it can be concluded higher possibility of debonding occurred when crack or failure started from cement-bracket interface compared to enamel-cement interface.

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