Fracture Mechanics Analysis of the Durability of Resin-Bonded Bridge — The effect of Resin-Bonded Bridge Design Parameters on Crack Growth along Adhesive Layer —

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The effects of resin-bonded bridge geometry on crack growth along the adhesive layer were analyzed by the use of elastic energy release rate g concept, together with the finite element technique. The values of g and the critical load for crack propagation in the adhesive layer are presented for various horizontal crack length a^* , safety factor n , and metal frame configuration and thickness t_m . Based on this analysis, suggestions for the design of resin-bonded bridge are suggested, in order to increase its durability.

Key words : Resin-bonded bridge, Crack growth, Energy release rate

INTRODUCTION

A bridge with an adhesive layer is known as the resin-bonded bridge. Though it is attractive, due to its simple configuration, the strength of the adhesive structure seems to need further studies from several points of view such as bridge geometry¹⁻³⁾, metal surface treatment⁴⁻⁷⁾, and the adhesive material itself⁸⁻⁹⁾. Previous papers¹⁻³⁾ on bridge geometry showed that the durability of the resin-bonded bridge under bending load is improved by using a metal frame with increased thickness and stiffness and by adding a wing to the metal frame. These studies assumed that the restoration was perfectly attached to teeth by the adhesive layer.

In the clinical application of resin-bonded bridge, it is usually assumed that a void exists between the restoration and tooth. Moreover repeated load together with chemical attack may yield microcracks in the adhesive layer or along its interfaces related to either the restoration or tooth. This porosity and these microcracks may develop into a large macrocrack under repeated and/or increased load, and eventually at a certain load level this main crack will detach the restoration. Thus the crack problem along the adhesive layer becomes an important issue for the durability of resin-bonded bridge, which has not been discussed in other studies.

Therefore the effect of bridge geometry on the crack growth along the adhesive layer is the first step in analysing this kind of problem. The elastic energy release rate concept will be applied to assess the critical force in crack propagation.

ANALYTICAL FORMULATION

Fracture mechanics

The stress $\sigma_{ij}(r, \theta)$ shows a singularity at the crack tip in elastic material, which is

expressed by¹⁰⁾

$$\sigma_{ij}(r, \theta) \propto \frac{K}{r^{\frac{\alpha}{2}}} f(\theta), \quad (1)$$

where (r, θ) denotes a polar coordinate system with the origin at the crack tip as shown in Fig. 1. The value of α is 0.5¹¹⁾ for a homogenous material, and K is the stress intensity factor¹⁰⁾.

The maximum stress criterion in crack propagation will give a critical load of zero as any finite load raises infinite stress at the crack tip. But in practice cracks do not propagate under the infinitesimal load.

In order to deal with this propagation problem, fracture mechanics provides three main methods. These are the stress intensity factor K , crack opening displacement COD and available energy release rate g . There are fixed relationships between them in an elastic homogenous body¹⁰⁾. The crack is assumed to propagate for the load when $K > K_{cr}$, $COD > COD_{cr}$ or $g > g_{cr}$, where the subscript “ cr ” denotes “critical”. These critical values are supposed to be material constants as a first approximation¹⁰⁾. The value of g_{cr} is equal to the specific surface energy of a newly made crack surface in a simple case. A complicated crack propagation such as the one in the case of composite materials requires not only surface energy but also other types of energy such as frictional work, plastic work, microcrack surface energy ahead of the main crack and debonded interface energy for evaluating g_{cr} . In case of the small scale yielding where the plastic region at the crack tip is quite small and most of the area around the crack tip is governed by equation (1) three methods could be applied without any practical modification. The focused crack in this paper could be considered to propagate along the interface between the metal restoration and the thermo-plastic adhesives in a brittle manner¹⁰⁾ with little plastic deformation. Thus any fracture mechanics concepts could be used theoretically with no restoration.

Fig. 1 Polar coordinates taken at the crack tip.

The finite element technique will be used for elastic calculations in this paper. The calculation of K needs α , which is not 0.5 for a crack along the bimaterial interface. This α might be obtained after tedious discussion by using the same finite element technique or by applying an alternative analytical method^[2].

The evaluation of COD also needs preliminary discussions to choose a reference joint. As both K and COD are usually obtained from the element the joint near the crack tip, a fine mesh geometry near the crack tip is necessary.

Thus the energy release rate g is selected to assess the durability of resin-bonded bridge. It means the change of potential energy due to the crack propagation and its reliable values can be obtained from a relatively coarse mesh geometry without any preliminary calculations and discussions.

Energy release rate g

The crack surface area is supposed to increase by δA under a constant load P as shown Fig. 2(a), which results in the increase of displacement δu at the loading point. The total strain energy stored in an elastic body is equal to the total work done by the external load. Thus the increase of strain energy δU is given by

$$\delta U = \frac{1}{2}P(u + \delta u) - \frac{1}{2}Pu = \Delta 0a'b' - \Delta 0ab = \frac{1}{2} \square abb'a' = \Delta 0aa' > 0 \quad (2)$$

as shown in Fig. 2(b).

Here the linear relation between load and displacement is assumed. On the other hand, the incremental work δW done by the external constant load P is as follows,

$$\delta W = P\delta u = \square abb'a' = 2\Delta 0aa' \quad (3)$$

Therefore the increase of potential energy $\delta \Pi$, which is defined by

$$\delta \Pi = \delta U - \delta W \quad (4)$$

Fig. 2 Crack growth under constant load.

becomes negative, that is,

$$\delta\Pi = -\Delta\sigma aa' \quad (5)$$

This released potential energy per unit area leads to the (available) energy release rate g , as follows,

$$g = -\lim_{\delta A \rightarrow 0} \frac{\delta\Pi}{\delta A} = \frac{\partial\Pi}{\partial A} \quad (6)$$

From Eqs. (2), (5) and (6) g is expressed by

$$g = \frac{\partial U}{\partial A} \quad (7)$$

The same result as Eq. (7) is obtained for the fixed end loading condition.

Figure 3 shows the way to obtain g using the finite element technique. First the constant

Fig. 3 Schematic figure for g with finite element technique.

load P_i is applied to the joint i of an elastic body with a crack of length a , and then the displacement u_i of the joint i is obtained. The total strain energy U_a becomes the sum of half the scalar product P_i and u_i .

$$U_a = \frac{1}{2} \sum_i P_i \cdot u_i \quad (8)$$

Next the total strain energy of the same elastic body with a slightly increased crack length $a + \delta a$, $U_a + \delta U_a$ is calculated from the solution $u_i + \delta u_i$ under the same loading condition as follows,

$$U_a + \delta U_a = \frac{1}{2} \sum P_i \cdot (u_i + \delta u_i) \quad (9)$$

Equations (7)~(9) yield g for the crack length a as follows,

$$g \left(= \frac{\partial U}{\partial A} \right) = \frac{1}{2t\delta a} \{ \sum P_i \cdot (u_i + \delta u_i) - \sum P_i \cdot u_i \} \quad (10)$$

where t is the thickness of the model.

Calculation model

A schematic figure of the resin-bonded bridge is shown in Fig. 4(a). A structural weak point of this bridge is the adhesive layer between the metal frame and tooth. The load is usually applied to the upper portions. Thus a crack is supposed to appear in and around the upper adhesive layer due to the load to porcelain. Therefore a two-dimensional finite element analysis will be performed for the most severely loaded upper portions.

Figure 4(b) shows two types of supporting conditions for this two-dimensional model. Figure 4(b-1) is realistic as it affords the elastic rotation as a whole while keeping a symmetry condition.

But this supporting system needs a very difficult preliminary calculation for the elastic spring constants of supports. In Fig. 4(b-2) elastic supports are replaced by fixed end conditions, which do not need values of elastic constants. Moreover the symmetry condition is replaced by the free end condition, which affords the elastic rotation as a whole. This paper will use the boundary condition in Fig. 4(b-2) as in Ref. 10.

Two types of resin-bonded bridge models were analyzed to assess the effect of a wing in the metal frame. Figures 5 and 6 show the finite element geometries for resin-bonded bridge models without and with a wing, respectively. The thickness of metal frame t_m varied as 0.5, 1.0 and 1.5 mm in both cases. The thickness perpendicular to these mesh geometries are all set to be 1.0 mm. Resin-bonded bridge models consist of abutment tooth with enamel and dentin, adhesive layer of 50 μ m thickness, Co-Cr alloy and porcelain.

The mechanical properties^{2,3,13)} are shown in Table 1. The constant load P is applied at the original center of the dummy, that is, the lower left side of porcelain in Figs. 5 and 6. The value of P is set to be 5 kg³⁾, which is severe for practical purposes. Both the left and right sides of the models are abbreviated in Figs. 5 and 6. The dummy and abutment tooth widths are 4 and 8 mm, respectively. The wing length is 1 mm in Fig. 6.

It is assumed there is crack growth along the interface between metal frame and adhesive layer by reference to previous reports^{1,14)}. The elastic work performed by the

Fig. 4 Resin-bonded bridge and its two-dimensional modelings.

Table 1 Mechanical properties of constituents used in the calculation

Material	Young's modulus (Kgf/mm ²)	Poisson's ratio
Co-Cr alloy	20,000	0.3
Resin	400	0.3
Enamel	4,000	0.3
Dentin	1,400	0.15
Porcelain	13,000	0.2

Fig. 5 Finite element geometry of resin-bonded bridge without wing.

Fig. 6 Finite element geometry of resin-bonded bridge with wing.

constant load P is first calculated for the bridge without any cracks. Then the crack is incorporated into the mesh geometry by separating elements one by one along the crack path, as shown by the thick line in Figs. 5 and 6.

Elastic calculations for the various crack lengths show the elastic work is related to the constant load P . The crack length varied from 0.125 to 1 mm with the interval δa of 0.125 mm in Fig. 5 and from 0.177 to 1.414 mm with the interval δa of 0.177 mm in Fig. 6.

Values of elastic energy for two adjacent crack length are inserted into Eq. (10) to obtain the energy release rate g . Nine elastic calculations are made to obtain eight values of g along the crack path for each t_m . As shown in Fig. 7 g 's with the same horizontal crack length component a^* are compared.

The computer system of the Research Institute for Applied Mechanics, Kyushu University, FACOM-M360AP was used together with a supplied program of the finite element technique.

Fig. 7 Horizontal component a^* of crack length a .

RESULTS

Effect of metal frame thickness

Figures 8 and 9 show the energy release rate g as a function of horizontal crack length a^* with a parameter of metal frame thickness t_m for $P=5$ kg. Suffices o in Fig. 8 and w in Fig. 9 to g denote bridges without and with wing, respectively. In the case where $t_m=0.5$ mm g_o in Fig. 8 increases rapidly just after the crack initiation and becomes large. Where $t_m=1.0$ and 1.5 mm g_o increases 10 to 20 percent more than g_o where $t_m=0.5$ mm for the same a^* . The g_w in Fig. 9 increases gradually for all t_m as a^* increases and its increase rate becomes large when a^* is larger than 0.5 mm. In all cases g increases as t_m decreases and a^* increases.

Effect of metal frame configuration

The difference between g_o and g_w , that is $\Delta g = g_o - g_w$, is shown in Fig. 10 for $P=5$ kg. It is positive within the calculated range and presents the maximum occurs when $a^*=$

Fig. 8 Energy release rate of resin-bonded bridge without wing, g_0 .

Fig. 9 Energy release rate of resin-bonded bridge with wing, g_w .

Fig. 10 The effect of wing: $\Delta g = g_0 - g_w$.

0.5 mm, which is the half of the wing length. Moreover it is shown that Δg decreases rapidly as t_m increases from 0.5 mm to 1.0 mm and is very small for 1.5 mm.

DISCUSSION

The author has paid attention to the energy release rate g for the interface crack between the metal frame and the adhesive layer as a function of metal frame configuration and thickness. The crack propagates if g is larger than its critical value g_{cr} . Calculated values of g gives us the following suggestions corresponding to the durability of resin-bonded bridge.

Effect of metal frame thickness

The value of $g_{o(w)}$ decreases as t_m increases and is very small when $t_m > 1.0$ mm. Thus the thick metal frame can suppress the crack propagation.

Effects of metal frame configuration

1) As g_0 is larger than g_w , the edge crack propagates with more difficulty in the resin-bonded bridge with a wing than without one after it initiates along the metal-side interface.

2) The value of $\Delta g (= g_0 - g_w)$ as a function of a^* reaches its maximum when $a^* = 0.5 \sim 0.625$ mm, which means that the wing is especially effective for this size of crack.

3) The value of Δg is much larger with a smaller t_m . Thus the wing is very effective for the thin metal frame.

Comparison between $g_{o(w)}$ and γ

A material constant g_{cr} could be equal to the specific surface energy γ as the crack propagates in a brittle manner. But in dental application chemical attack and repeated loading may damage the adhesive interface. Moreover microscopic spaces may exist due to the manufacturing process. These will result in reduced effective surface energy. Therefore the safety factor n is used, that is,

$$g_{cr(n)} = \frac{\gamma}{n} \quad (11)$$

Here, γ is taken to be $40 \text{ J/m}^2 = 4.06 \times 10^3 \text{ kgf/mm}^{10}$.

Figure 11 shows calculated g_0 and g_w and practical mechanical constant g_{cr} with various n . There exists an interface crack with a^* of around $50 \mu\text{m}$ due to various reasons which were mentioned in relation to the reduced specific surface energy. In the case where $a^* = 50 \mu\text{m}$ g_0 with $t_m = 0.5$ mm is less than $g_{cr(1)}$ and larger than $g_{cr(2)}$ and $g_{cr(3)}$, the interface crack does not propagate for $n=1$ but it does in damaged adhesives with $n=2$ or 3. Other values such as g_0 for $t_m = 1.0$ and 1.5 mm and g_w for all t_m are less than $g_{cr(3)}$, which means that the interface crack does not propagate. In cases of more severe conditions such as $a^* = 100 \mu\text{m}$ only g_0 with $t_m = 1.5$ mm and g_w with $t_m = 1.0$ and 1.5 mm are less than $g_{cr(3)}$, where the interface crack does not propagate.

Critical load P_{cr}

In Fig. 11 P is set to be 5 kg. The critical load P_{cr} could be obtained for various a^* , t_m , n and configurations as follows. The displacement at the loading point is proportional to P . Then the released energy is proportional to P^2 . Thus P_{cr} is represented by g_{cr} and calculated $g_{o(w)}$ when $P=5$ kg, that is,

$$\frac{P_{cr}}{5 \text{ kg}} = \sqrt{\frac{g_{cr}}{g_{o(w)}}} \quad (12)$$

Critical loads are shown in Table 2 when $\gamma = 40 \text{ J/m}^2$ and $n=3$. Thus it is desirable to adopt the metal frame with a wing and thickness layer of 1.5 mm from the energetic condition for the practical specific surface energy γ of 40 J/m^2 and with safety factor of 3.

Suggestions for the designs of resin-bonded bridge

Suggestions for the design of resin-bonded bridge are suggested here in order to increase the durability of the resin-bonded bridge following what has been discussed above.

Fig. 11 Comparison between $g_{0(w)}$ and g_{cr} .Table 2 P_{cr} for various a^* , t_m and configurations; values in () denote P_{cr} for resin-bonded bridge with wing

a^* (μm)	t_m (mm)	0.5	1.0	1.5
50		3.96 (6.71)	6.71 (9.82)	11.62 (18.37)
100		2.64 (4.59)	4.59 (7.21)	7.83 (12.99)

(kg)

- 1) It is desirable that the metal frame thickness t_m be larger than 1.0 mm.
- 2) The wing is particularly effective for the thin metal frame with t_m around 0.5 mm.

CONCLUSIONS

Fracture mechanics was successfully applied to the crack problem in dental restorations. The effect of resin-bonded bridge design parameters on the crack growth between metal frame and adhesive layer was investigated using the energy release rate g , which leads to the

following conclusions.

(1) Both energy release rates without and with wing, being denoted by g_0 and g_w , respectively, decrease as metal frame thickness t_m increases, and they are very small when $t_m > 1.0$ mm.

(2) The value of g_0 is larger than g_w , and their difference $\Delta g (= g_0 - g_w)$ as a function of horizontal crack length a^* reaches its maximum when $a^* = 0.5 \sim 0.625$ mm.

(3) The value of $g_{0(w)}$ compared with $g_{cr} = \gamma/n$ is used to obtain the critical load P_{cr} , where γ and n denote the surface energy and safety factor for damage, respectively.

It is shown that t_m should be larger than 1.0 mm and that the wing is particularly effective for cracks with length less than half that of the wing.

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コンポジットレジン用レオメータにより 4 種類の市販小窩裂溝充填材の操作時間、硬化時間を測定した。また、人の抜去歯牙の小窩裂溝に充填された材料の硬化中の温度上昇を熱電対を用いて調べ、さらに、高速液体クロマトグラフを使って硬化後の未反応物質の分析を行った。

23°C でのそれぞれの材料の操作時間は 0.52~1.09 min の間であり、そしてまた 32°C での硬化時間は 0.91~1.38 min の間であった。0.5 mm の厚さで硬化さ

せた時、髓室蓋から 1.2 mm 離れたデンチン部分での温度上昇は 0.18~0.21°C の間であった。未反応物質は、硬化前後のそれぞれの溶液で測定されたクロマトグラフの面積比で計算され、0.5 mm の厚さの試料では、それぞれの材料で 19.7~45.8% の範囲であった。

本実験中の小窩裂溝充填材では、硬化時の温度上昇の歯髄に対する影響はほとんどないと思われる。

充てん用コンポジットレジンに関する研究

—第 3 報— 光重合型コンポジットレジンの L 細胞に対する毒性試験

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現在市販されている 18 種類の光重合型コンポジットレジンについて、マウス由来の培養細胞に対する各材料の細胞毒性試験を行なった。細胞障害の程度は、細胞死滅を含む核濃染領域と細胞形質に萎縮がみられる領域の 2 領域にわけ、それぞれの領域の面積で表示した。また、各材料の硬化物中に含まれる未反応物の量を高速液体クロマトグラフを用いて定量し、未反応物量と細胞障害がみられる領域との関係を調べた。その結果、4 種類の材料(パルフィークライト、プリズマフィル、プリズマフィ

ルコンピューール、パイロフィルライトボイド)を除く他の材料間では、硬化体中の未反応物量と細胞障害を引き起こす領域との間に相関がみられ、未反応物の増加に伴って細胞障害を起こす領域が大きくなることがわかった。除外した 4 種類の材料については、硬化体中の未反応物量は少ないにもかかわらず、細胞障害を起こす領域が著しく大きくなっている。この理由については現在検討中である。

接着性ブリッジの耐久性に関する破壊力学的解析

——接着性ブリッジの設計要因が接着層でのき裂成長に与える影響——

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有限要素法にもとづく破壊力学的手法によって、接着性補綴物の設計条件と接着材層に発生するき裂成長との関係をエネルギー解放率 g の概念を用いることにより解析した。解析は接着材層でのき裂成長に伴うエネルギー解放率とクリティカルロードの値が、水平的なき裂長さ a^* 、安全率 n 、メタルフレームの構造および金属の厚さのファクターによりどの様に変化するかにより行なった。解析の結果、 g はメタルの厚みが増すと減少し、

1.0 mm 以上では非常に小さくなった。また隣接面にウィングを設定すると設定しない場合に比べ g は小さくなり、その差 Δg はウィング長の半分程度で最大となった。そして Δg は、金属厚みの増加に伴ない減少した。結果とクリティカルロードを用いた考察により、接着性補綴物の耐久性を向上させる為のブリッジの設計要因について検討を行ない呈示した。