The research on the dental bridge model-making process based on the curing shrinkage epoxy and residual stress reduction

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ABSTRACT

Elderly people suffer from more and more teeth problems. The tooth-implant-supported prosthesis provides a reliable solution to missing teeth patients. The proper dental prosthesis design to prevent overstress is essential due to the mechanical characteristics of the dental bridge abutments are different. The finite element method is widely applied, but proper experimental validation is required. The curing shrinkage epoxy is applied for the photoelasticity measurement because its mechanical property is close to the cancellous bone. A series of process developments, including mold design, residual stress releasing and artificial soft film making, is accomplished in this research to simulate the mechanical response of dental bridges in practice. The process is proven and can be accomplished at the dentist’s workshop. The transmission photoelasticity technique is applied to measure the residual stress distribution and it nondestructively provides the continuous improvement guideline. The model-making procedure and tools are proven to be available at the dental workshop. Following the model-making procedure, the dental bridge model shows a low residual stress level that the photoelasticity system cannot detect. Excellent reproducibility of the proposed procedure has been validated.

1. INTRODUCTION

Elderly people often suffer from tooth missing problems, which might cause insufficient food intake and induce nutrition imbalance. For a partially edentulous patient, there are 3 treatments methods to resolve, including removable partial denture, dental implant and supported prosthesis. Clinically, when treating patients with Kennedy Class I or Class II partially edentulous arch, the use of dental implants can avoid the issues of wearing removable partial dentures and improve the chewing function effectively. However, some patients cannot apply a sufficient number of dental implants because of the anatomical factors caused by bone absorption. The dental bridge between the natural teeth and dental implants is a practical option, as illustrated in Fig. 1. The implant fixture (Fig. 1a) is established first, and then the tooth (Fig. 1b) is prepared for the dental bridge restoration (Fig. 1c).

A clear difference can be found between the mechanical condition of the natural tooth and dental implant to the spongy cancellous bone. The natural tooth is connected in the alveolar bone by root with the periodontal ligament (PDL), a soft material around the root. The dental implant is fixed by the titanium implant fixture, and there is no soft material around the fixture due to the osseointegration nature. Hence, in the dental bridge, under occlusal loading, the stress distribution is different around the natural tooth and implant. Therefore, improper dental bridge design results in a stress concentration, which will cause continuous pain to the patient during biting and induce the bone loss around implant and facture of the natural tooth, dental bridge [1] to the natural tooth, dental bridge or implant.

Due to the geometrical complexity, the finite element method is often applied to investigate the stress distribution of the biological implants. Su et al. [2] have worked together with the medical doctor to establish a 3-dimensional (3D) finite element model to investigate the femoral improper cut effect with the implant on the surgery with a static standing condition. The simulation result suggests the cutting strategy during the surgery. Shen et al. [3, 4] applied the finite element method to study the flexibility of the self-expandable tapered stent. Chao et al. [5] applied the finite element method to obtain the stress distribution due to the changes of the distal screw alignment in relation to the Gamma nail and the femoral shaft. Chaichanasiri et al. [6] investigate the mechanical response of the dental implant-retained crown and its adjacent nature teeth using a 3D finite element
model. Moreover, due to the spongy characteristics of the cancellous bone, the stress distribution of the adjacent natural teeth will not be influenced by the dental implant.

Correia et al. [7] have applied the 3D finite element method to model the human mandible to study the stress distribution under different cancellous bone densities. Merdji et al. [8] investigated the stress distribution of a single molar tooth by conducting finite element modeling. Under the proper loading condition, a von Mises stress level of 4-6 MPa at cancellous bone is obtained. Dhatrak et al. [9] applied the finite element to understand the stress distribution pattern around the implant–bone interface. The finite element model is applied with the photoelasticity validation. Under the vertical loading of 300 N upon a single implant, a max von Mises stress level of 5–6 MPa, located around the apical region of the implant, is obtained from simulation and photoelastic measurement.

On the other hand, the finite element model requires experimental validation. Nowadays, the photoelasticity method is widely applied because it can depict the stress pattern under the particular loading. Cehreli et al. [10] and Canto-Naves et al. [11] applied the epoxy resin to study the stress distribution of the implants under vertical loading. The selection of the epoxy resin is because it is chemically stable with high manufacturability, and the mechanical characteristic is close to cancellous bone. Moreover, to represent the boundary condition of the natural tooth and the dental implant, technical approaches are conducted. Martins [12] applied polyether to represent the PDL, which is an essential factor for the vertical displacement of the natural teeth under loading. However, the residual stress around the top interface of the model remains. Markarian et al. [13] built two kinds of photoelasticity models of 3 dental implants and investigated the stress distribution of the central implant with different angles. In their research, the gypsum case is applied to reduce the residual stress induced by the drilling process of the dental implants. Huang et al. applied the finite element method (FEM) to analyze the stress pattern of the dental bridge under external biting loading. The results show that the maximum stress is located at the apical implant region [14].

Through the literature studies, very few knowledge is revealed about the manufacturing method for a photoelastic model of a dental bridge with both natural tooth and dental implants. Therefore, this research investigates the manufacturing method for the dental bridge model to reduce the residual stress caused by the shrinkage of the epoxy resin and the drilling for the implant fixture. This model can depict the stress distribution under biting loadings and provide experimental validation for the finite element model. Note that, although drilling is required for the dental implant process, the osseointegration process will be triggered as soon as the high stress induced by screwing the titanium fixture is into the cancellous bone [1]. The residual stress will be reduced gradually by new bone tissue grown around peri-implant [15] and becomes negligible after the dental bridge process is accomplished.

This paper will be organized as follows: the problem statement and the literature survey are listed in Section 1. The following Section 2 describes the basic photoelasticity and curing shrinkage of epoxy. Section 3 depicts the photoelastic meter and the computer numerical control (CNC) machine that we applied in this research. Next, Section 4 describes the materials and the model-making procedure. The approaches, including reducing the residual stresses induced by the epoxy curing shrinkage and the drilling process, will be described. Section 5 describes the residual stress reduction approaches validated by the photoelasticity. Section 6 describes using the approaches and applying the photoelasticity results to validate the finite element model. A brief conclusion will then summarize this paper.

2. FUNDAMENTALS

2.1 The photoelasticity

In optically anisotropic materials, such as a plastic under mechanical stress, when a ray of light is incident, a double refraction phenomenon can be found, which is revealed as the polarization into two rays taking slightly different paths. The retardation of these two paths, called the fast and slow rays, can be mathematically described as \( \delta = h(n_1 - 1) \), where \( i = 1, 2 \) represents the fast and slow rays, \( n \) is the reflection coefficient of fast and slow rays and \( h \) is the thickness. The relative retardation can be derived as:

\[ \delta = \delta_1 - \delta_2 = h(n_1 - n_2). \]  

(1)

Considering a plastic under loading, the photoelasticity can be described by the 2-dimensional stress-optical law under the plane stress assumption, as

\[ n_2 - n_1 = C(\sigma_1 - \sigma_2). \]  

(2)

where \( \sigma_1 \) and \( \sigma_2 \) are the principal stresses and \( n_1 \) and \( n_2 \) are the reflection coefficient along the principal axis. \( C \) is the relative stress-optical coefficient. Assume the wavelength of the incident light is \( \lambda \), and the phase difference \( \Delta \) can be written as:

\[ \Delta = \frac{2\pi}{\lambda} \delta. \]  

(3)
The dentist applies the parametrical finite element modeling technique to acquire the best operation parameters, such as implant angle and dental bridge/crown design. And a good model validation is required before the application of the parametrical model. As mentioned previously, different models might be applied because of the case dependency and prosthesis material/technology improvement. The dentist and professionals should be able to conduct these processes in the independent workshop. In this research, the measurement setup, the model-making procedure and tools are available at the actual dental workshop. The model-making process is accomplished by close collaboration between engineers and dentists. The accuracy and the influence of the key processing parameters are investigated. The proposed model-making method can be applied to the osseointegration-based prosthesis technologies.

This research applied the transmission photoelasticity setup. This is because the requirement of the light orthogonality is low due to the light incident into the birefringence material only once. Moreover, a circular polariscopetransmissionsetup,illustratedinFig.4,istableandcontrollableachievespeedy,non-destructivewaytomeasurethestressdistributionofthedentalbridgemodel.

The first quarter-wave plate is placed between thepolarizerand the specimen, and the second quarter-wave plate is placed between the specimen and the polarizer at the observer side. The effect of adding the quarter-wave plate after the source-side polarizer is that we get circularly polarized light passing through the sample. The observer-side quarter-wave plate converts the circular polarization state back to linear before the light passes through the analyzer. Hence, theisochromatic and not theisoclinicareobserved, and this eliminates the problem of differentiating between theisoclinicand theisochromatic. The circular polariscopetransmissionconcepthasbeenrealizedasFig.4a. Besides the circular polarization requirements, a rigid frame is designed to be able to load the specimen.

A homemade desktop horizontal milling machine with theCNCisestablishedtoperformastableandcontrollablecuttingtothemodel-makingprocess,asshowninFig.4b. ThemainbodyofthemachineismadeofSS0Csteeltoensurestabilitywithlightweight.AZKmach3CNCcontrolboardisappliedfora4-axiscontrolwithahigh-speedspindleandairconing.
In this research, a thermoset plastic epoxy which is the mixing of the epichlorohydrin \( (C_3H_5O_10) \) and bisphenol-A \( (C_{15}H_{16}O_2) \) with the amine hardener, is applied. Among the materials in the dental bridge model, Young’s modulus of the cancellous bone is approximately 1370 MPa \[11\], and the material property is approximately 1500 MPa when the mixing procedure is well-controlled. More, this epoxy is highly transparent for the photoelasticity measurement. Dhitraka et al. \[9\] have proven the similarity of the epoxy to the cancellous bone by both experiment and finite element method. The chemical composition can be written as:

\[
\text{where } 0 > n > 25.
\]

The epoxy mixture is then poured into the model mold, as shown in Fig. 5 (B6). The epoxy model is then cured under the 25°C and 20% relative humidity for 7 days. Note that the epoxy model is cured with the top surface inverted and faced to the wax, and therefore, the epoxy curing shrinkage is constrained, which decreases the accumulated residual stress. The molds are removed after the curing process is completed.

After the epoxy curing is completed (Fig. 5 (C1)), the implant substitution is then removed (Fig. 5 (C2)), the high-speed dental handpiece is applied to enlarge the hole (Fig. 5 (C3)), and the implant is then screwed into the model (Fig. 5 (C4)). This procedure can reduce the high stresses by the direct drilling process because these stresses are released by the osseointegration procedure in practice. Meanwhile, this procedure also eliminates the unnecessary hydrogen bond that generates at the metal/epoxy interface \[17\] when epoxy is cured with a metal implant embedded. Then, the natural tooth is modified by the high-speed dental handpiece to fit the dental bridge. Moreover, the peripheral epoxy of the natural tooth and dental implant is slightly removed to release the residual stress accumulated at the interface among epoxy, tooth/implant, and wax (Fig. 5 (C5)). These operations, which are shown in Fig. 5 (C3)-(C6), are accomplished by professional dentists who are experienced with dental implantation. After the dental bridge is applied to the model (Fig. 5 (C6)), the edge of the epoxy is removed by the CNC machine (Fig. 4b) to release the residual stress during the curing process, as illustrated in Fig. 5 (C7).

### 4.2 The artificial PDL procedure

The PDL, a soft film around the dentin, provides mechanical flexibility under the biting loading. However, the PDL is destroyed during teeth removal. The creation of the PDL substance into the model is essential. Fig. 5 (A) shows the procedure to generate artificial PDL. The natural tooth is first cleaned (Fig. 5 (A1)), and a thin thermal resistant tape is applied at dentin (Fig. 5 (A2)). The structure is immersed into a hot wax (Fig. 5 (A3)) and creates a hole (Fig. 5 (A4)). Ethylene vinyl acetate (EVA)-based hot-melt adhesive is applied to the hole by the hot glue gun (Fig. 5 (A5)). Before the EVA glue is cured, the natural tooth is inserted into the EVA-filled hole (Fig. 5 (A4)) and
removed. A uniform and thin EVA will be carried by the tooth (Fig. 5 (A6)).

4.3 The implementation
The realization of the dental bridge model proposed by this research is a cooperation of mechanical and dental experts. The epoxy curing work has been conducted as illustrated in Fig. 6, including the hot wax preparation (Fig. 6a), pouring the wax into the wax mold (Fig. 6b), placing the natural tooth and implant substitution (Fig. 6c) and placing the epoxy mold (Fig. 6d). Then, the epoxy is filled into the mold cavity (Fig. 6e) and cured (Fig. 6f). Afterward, all the molds and the implant substitution are removed (Fig. 6g). Next, the dental implant is implanted by the dentist with professional procedures, including the hole cleaning (Fig. 7a), the dental implant installing (Fig. 7b), and the tooth shape modification (Fig. 7c).

Fig. 8a shows the tooth after the tooth shape modification, as indicated by Fig. 7c. The peripheral of the natural tooth and the dental implant at the epoxy surface is partially removed to reduce the residual stress accumulated by the curing process. The edge of the hexagonal epoxy is removed by the CNC machine after the dental bridge is applied.

5. PHOTOELASTICITY RESULT AND DISCUSSION

5.1 The reduction of residual stresses
Due to the epoxy curing shrinkage nature shown in Fig. 2, we investigate the contribution of the epoxy mold to the residual stresses. As illustrated in the left-hand side of Fig. 9a, the epoxy mold was initially designed as a rectangular shape. After the epoxy material was filled into the mold and cured, Fig. 9b shows the shape, and 2 little protrusions occur at the left-hand side of the top surface due to the shrinkage restriction of the mold with respect to the open side. As shown in Fig. 9c, an apparent stress concentration at four corners of the cured sample is discovered under the photoelastic measurement. According to Eq. (4), the stress of 1.1 MPa is obtained under the circumstance that the material fringe value ($f_{m}$) is 8.33 (N/mm) and thickness of 7.5 mm. Comparing to stress distribution obtained from Dhatrak et al. [9], where the maximum von Mises stress under biting loading is around 4–6 MPa, this residual stress of this model is significantly high.

The shape of the mold is modified to hexagonal, as indicated on the right-hand side of Fig. 9a, to reduce the residual stress. The appearance after curing is shown in Fig. 9b, and no
obvious structure defect is found. As indicated in Fig. 4b, the CNC milling machine is applied to remove the edge of the hexagon. Table 1 lists the CNC milling machine settings. Because of the heat generated by the milling process, the test 1 sample from Table 1 shows high residual stress at the cutting edge, such as the left-hand side of the sample. This residual stress can be decreased by increasing the feeding rate. When the feeding rate of the CNC milling machine achieved 700 mm/min, the residual stress is too low to be detected by the photoelastic setup.
Dental bridge model-making process

Figure 8 The final dental bridge model (a) before the bridge and (b) after the bridge and edge milling.

Figure 9 The mold shape and residual stress.

Table 1 The CNC milling parameters concerning the residual stresses.

|                        | Test 1 | Test 2 | Test 3 |
|------------------------|--------|--------|--------|
| Spindle rotation (rpm) | 1500   | 1500   | 1500   |
| Feeding rate (mm/min)  | 100    | 300    | 700    |
| Photoelasticity result | ![Image](#) | ![Image](#) | ![Image](#) |

Next, the residual stresses induced by the inserting of the natural tooth and the dental implant are discussed. The natural tooth was first immersed into the uncured epoxy model, and epoxy is cured top side up. Then, the implant was installed by directly drilling. The photoelastic result is shown in Fig. 10a, where apparent residual stresses at the peripheral of the tooth and the apical implant’s region are found at the value of 0.53 MPa.

The residual stress at the peripheral of the natural tooth is reduced by changing the curing status to the top side down using wax (Fig. 5 (B5)). Moreover, the epoxy of the peripheral tooth is
removed by the high-speed dental handpiece. Furthermore, the stress at the bottom of the implant is reduced by applying the implant substitute with less drilling, as indicated in Fig. 5 (B6) and Fig. 5 (B3). After the treatment, the stress pattern is obtained as Fig. 10b, and no clear residual stress can be found.

The reproducibility of the proposed procedure, illustrated in Fig. 5, is studied. Three dental bridge models, which are handmade every other week, are listed in Table 2. Different natural teeth are applied, as indicated in the second column of Table 2. Although there are fringes on the boundary at 3 trials before loading, all 3 models exhibit low residual stresses and similar maximum stress, approximately 2.13 MPa at the natural teeth apex and apical implant region, under vertical 300 N loading upon the dental bridge.

The stresses reported by Dhatrak et al. [9] are approximately 4–6 MPa, where the external loading is applied upon a single dental implant. In our research, the dental bridge with two supports, including a natural tooth and a dental implant, exhibits maximum stress of 2.13 MPa, similar to the literature.

6. APPLYING THE MODEL TO VALIDATE THE FINITE ELEMENT MODEL

A 3D finite element model, including the dentin and PDL of the natural tooth, the fixture of dental implant and dental bridge, is established, as shown in Fig. 11a. There are 88 291 solid elements with mesh density control. Moreover, high mesh density is applied to describe the geometrical characteristics of the dentin and the implant. The linear elastic material properties are applied to the model, as listed in Table 3. The bottom of the model and the sidewalls are fixed in the normal direction. A total vertical loading of 300 N is applied on top of the dental bridge, as shown in Fig. 11b.

In Fig. 12a, a photoelastic measurement of the model similar to the finite element is conducted, following the procedure shown.
Dental bridge model-making process

**Figure 11** (a) The 3D finite element model and (b) its loading/boundary conditions.

**Table 3** The material properties in the finite element model.

| Functional parts                  | Material      | Young’s modulus (MPa) | Poisson’s ratio |
|-----------------------------------|---------------|------------------------|-----------------|
| Implant fixture                   | Titanium      | 117 000                | 0.35            |
| Cancellous bone                   | —             | 1370                   | 0.3             |
| Cortical bone                     | —             | 13 700                 | 0.3             |
| PDL                               | —             | 170                    | 0.45            |
| Filler (between the dentin to the bridge) | Adhesive     | 11 000                 | 0.35            |
| Dentin                           | —             | 18 600                 | 0.31            |
| Dental bridge                     | Ni-Cr alloy   | 204 000                | 0.3             |

**Figure 12** The validation of the finite element model by the photoelastic measurement.

in Fig. 5. The maximum stress of 2.13 MPa is obtained under the vertical 300 N loading at the apical implant region, which coincides with dentist’s clinical experience [14]. The left-hand side of Fig. 12a shows the stress distribution of the natural tooth, and the right-hand side does the dental implant. On the other hand, the finite element model is solved by ANSYS version 19.2 solver, and the von Mises stress distribution is shown in Fig. 12b. Comparing to Fig. 12a and b, a good agreement is achieved. The stresses around the natural tooth apex and apical dental implant region are both 2.31 MPa, in both photoelastic measurement and finite element. The stress patterns of these two are similar as well.

7. CONCLUSION

The dental bridge can be applied to patients who suffer from bone absorption to improve oral chewing function. The
mechanical characteristics of the natural tooth and dental implant are very different in the cancellous bones. A proper dental bridge design is essential to prevent the high-stress concentration because excessive stress might cause oral pain, even the fracture of the natural tooth and dental implant. Applying the finite element method to study the stress distribution of the dental bridge design under the biting loading is a common approach, but a finite element model requires proper experimental validation.

In this research, a dental bridge photoelastic model-making procedure is developed to efficiently reduce the residual stress induced by the curing shrinkage of the epoxy and the drilling process during the installation of the dental implant. The measurement, model-making procedure, and tools can be available at the dental workshop. The procedure, illustrated in Fig. 5, including the epoxy curing and model modification, is a close collaboration between the mechanical expert and professional dentist. The photoelasticity technique is applied to measure the residual stress distribution nondestructively and provides the continuous improvement guideline.

The accuracy and the influence of the key processing parameters are investigated. The proposed model-making method can be applied to the osseointegration based prosthesis technologies. The shape of the mold is optimized in hexagonal due to the epoxy curing shrinkage characteristics, and the CNC milling is applied with a high feeding speed to release the residual stresses and prevent the milling heat accumulation. Moreover, an artificial PDL around dentin is made with uniform thickness to present the mechanical characteristics of the natural tooth in the cancellous bone. Following the model-making procedure, the dental bridge model shows a low residual stress level that the photoelasticity system cannot detect. Moreover, these models exhibit excellent reproducibility with the allowable maximum stress of 2.13 MPa around the natural tooth apex and apical implant region, similar to the one obtained from the literature [8, 9].

A finite element model of the dental bridge with the natural tooth and dental implant is then established. When a vertical 300 N loading is applied upon the dental bridge, the overall stress pattern at the cancellous bone is very close to the one obtained from the epoxy under the photoelastic measurement. Moreover, the location and value of the maximum stress value are also identical between the experimental and simulation results.

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