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A two-stage shape optimization process for cavity preparation

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ABSTRACT

Objectives. Clinical data indicate that previously restored teeth are more likely to fracture under occlusal loads. The reason for this is attributed to the high stresses at the tooth-restoration interface, especially following debonding of the restoration from the tooth. This work aims to minimise these interfacial stresses by optimizing the cavity shape using modern shape optimisation techniques.

Methods. Shape optimisation methods based on the principle of biological adaptive growth were incorporated into a finite element program and used to optimize the design of cavity preparations as previous work had successfully used one such method to minimise stresses at the internal line angles of conventional restorations with defective bonds. The overall shapes of the cavity preparations were maintained while the profiles of the internal line angles were modified. In the present study, the overall shape of the cavity preparation was also subject to modification in the optimization process. A topological optimization method which placed the restorative material according to the stress distribution was first used to obtain a draft design for the cavity shape, assuming perfect bonding at the tooth-restoration interface. The draft shape was then refined using the method employed in the previous study, to allow for deterioration in the interfacial bond strength. These optimization methods were incorporated into the commercial finite element package ABAQUS as a User Material Subroutine (UMAT) to automate the optimization process.

Results. Compared with the conventional design, the stress level at the tooth-restoration interface in the optimized design was reduced significantly, irrespective of the bonding condition.

Conclusions. Finite-element based shape optimization methods provide a useful tool for minimizing the interfacial stresses in dental restorations. The longevity of restored teeth using the optimized designs is therefore expected to be prolonged.

1. Introduction

There are many factors that cause failure of dental restorations. In a survey of 3455 restorations [1], secondary caries was found to be the most common reason for replacement (36%, 52% and 41% for composite, glass ionomer and amalgam, respectively), while fracture of tooth or restoration and lost composite restorations were the other two main causes.

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In another survey involving amalgam and composite resin restorations [2], the main reasons for failure were found to be caries (34%), endodontic treatment (12%) and fracture of the tooth (13%). Caries was found to be more common in composite restorations, while fracture of the tooth was more common in amalgam restorations. This was attributed to the fact that amalgam restorations are not adhesively bonded to the cusps, causing them to be more susceptible to cracking from the highly stressed internal line angles [2].

Secondary caries occurs at the margin of an existing restoration. In amalgam restorations, marginal fracture is considered as a precursor to secondary caries [3]. Research suggests that reducing marginal fracture could reduce the risk of secondary caries in teeth restored with amalgam [4]. Even in the absence of secondary caries, marginal fracture may lead to premature replacement of the restoration [3]. Marginal fracture, therefore, plays an important role in the failure of amalgam restorations. For composite restorations, an analysis of the findings of a multi-centre clinical trial revealed that restorations with marginal deterioration at year 3 were more likely to have failed by year 5 than restorations without marginal deterioration at year 3 [5]. There are many reasons that can cause marginal deterioration. Experiments have shown that both occlusal loading and shrinkage of composite undermine marginal integrity [6,7], with the stresses produced by these mechanisms causing failure of the tooth-restoration interface.

Much work has been carried out to explore methods of reducing marginal deterioration. By means of finite element analysis, Ausiello et al. [8] found that an appropriate adhesive layer thickness in a composite-restored tooth could lead to maximum shrinkage stress relief and improved interface integration. More flexible restorations were also shown to reduce the shrinkage stress magnitude and produce a more uniform stress distribution in the adhesive layer [9,10]. However, the materials and their interfaces also need to withstand the stresses due to occlusal loading.

Other studies have addressed the influence of cavity shape on the magnitude of the interfacial stresses. An ideal cavity shape should minimise stress concentrations along the tooth-restoration interface due to sharp angles or differences in material properties. If the interfacial stresses can be kept lower than the mechanical strength of the bond, marginal deterioration in a composite restoration can be expected to reduce, thus prolonging the lifetime of the restoration. Moreover, a lower stress level along the interface, with or without bonding, could also reduce the likelihood of fracture of the restoration and tooth [2]. The cavo-surface angle (CSA) and amalgam margin angle (AMA) were considered to be important factors that might affect the marginal integrity of amalgam restorations [11]. Research has shown that cavity walls at 90° to the tooth surface would provide a maximum bulk of amalgam in the form of a butt joint [12]. In such restorations the enamel rods will be parallel to the cavity wall. A CSA of 105°–115° and an AMA of at least 70° were clinically considered to be practical and sufficient to minimize the risk of enamel fracture [13]. The effects of the cavity configuration factor (C-factor), i.e. the ratio of the bonded surface area in a cavity to the unbonded surface area, and the remaining dentine thickness (RDT) on shrinkage stress development have been studied in composite restorations [14–16]. Results from these studies have shown that restorations with larger diameters and depths, i.e. higher C-factors, generated higher levels of shrinkage stress and microleakage. For occlusal loading, finite element analysis has also shown that the stress distribution in teeth with deep cavities is unfavourable [17].

Mondelli et al. [18] reported the fracture strength of maxillary amalgam-restored premolars with three types of cavity preparation – Class I, Class II and Mesiocclusodistal (MOD) cavities. Different buccolingual isthmus widths (one fourth, one third, and one half of the intercuspal distance) were considered. A compressive axial load was applied on the test teeth via a steel sphere of 4 mm in diameter. The results showed that all occlusal cavity preparations decrease the strength of teeth in proportion to the width of the preparation. The restored teeth with the narrower isthmus width resulted in better fracture resistance for the same preparation.

Some new cavity shapes were proposed by Porte et al. [19] who investigated shrinkage stresses. Cavities with large CSA, which were considered to lead to low stress concentrations near the free surface, resulted in better marginal integrity. A follow-up finite element study using axi-symmetric models supported these findings [20]. Similar cavity shapes were also investigated by Hembree [21] who measured microleakage in composite restorations with different carvo-surface designs. His results, however, indicated that etching the CSA and applying enamel bond were more important than the type of cavity shape used in minimizing microleakage.

Douvitsas [22] examined the width of the gap at the cervical wall following cyclic thermal loading in Class II composite resin restorations with rectangular and spherical cavity designs. Human molars were prepared for each cavity design by two different procedures, with or without etching and bonding. After restoration, the specimens were stored for 24 h, and then thermally loaded for 1500 cycles. The results indicated that the gap widths in the spherical cavities were smaller than those in the rectangular cavities, irrespective of the restorative material and procedure used. Moreover, the restorations placed with the use of etching and bonding agents recorded the smallest gap width compared with the other groups.

A saucer-shaped cavity design was proposed and investigated for composite restorations [23–25]. In a clinical trial, 51 preparations with such a cavity shape were completed and evaluated annually. Observations up to 10 years indicated that 70% of the restorations were acceptable for continued use [24]. The authors concluded that the saucer-shaped preparation was preferable to the box preparation in composite restorations. A more recent study compared the survival of restorations placed in saucer-shaped cavities to that of restorations placed in tunnel preparations [25]. After a mean service life of 28.8 and 30.3 months, the proportion of the tunnel and saucer-shaped restorations survived was 46% and 76%, respectively. Moreover, saucer-shaped restorations showed lower caries development than the tunnel restorations after an observation period of 24 months.

The alternative cavity shapes proposed in the above works were mostly based on experience and intuition of the investigators. More recently, attempts have been made by Proos et al. [26] and Couegnat et al. [27] at applying modern shape