Polymerization and loading stress distribution in adhesive resin-based composite class II restorations
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CHAPTER 1

Introduction

Restoring a damaged tooth means reconstructing the anatomy, repairing the strength as far as possible and above all protecting the exposed dentine against bacterial invasion. Marginal leakage in restored teeth is considered as the main reason for recurrent caries and replacement of the restoration (Brännström, 1982). Seal of the interface between the restoration and the cavity walls can be achieved if the restorative material adapts the tooth structure perfectly. Unfortunately perfect and lasting adaptation of the various dental restorative materials to tooth structure is extremely difficult to achieve and in practice also very hard to maintain with time. The mismatch of the essential material properties, such as dimensional stability and module of elasticity at both sides of the restoration's interface is the main reason for this. Particularly the popular restorative resin-based composites shrink considerably during setting, whilst the materials deform unequally during functional loading and temperature fluctuations. Since the introduction by Buonocore (1955) of bonding to tooth enamel, a powerful tool has been added to the dental profession to achieve perfect and durable sealing. This bonding is based on infiltration of the uncured resin into enamel surface porosities, obtained by etching the non-homogeneous structure with relatively strong acids (e.g. 37% ortho-phosphoric acid). After hardening of the resin, a strong and reliable micro-mechanical retention of the resin-based composite to tooth enamel can be obtained.

However in reality, the caries process often proceeds through the enamel towards the dentine, where bonding is essentially more
difficult (Bowen, 1982). Excavation of the affected tooth structure may lead to a situation where little enamel is left and dentine forms the main part of the substrate to bond on. In particular in mesio-occlusal (MO), distal-occlusal (DO) or mesio-occlusal-distal (MOD) cavities (Class II), retention based on reliable bonding to dentine is required. Since most of the available resin-based composites are hydrophobic, whilst dentine is essentially hydrophilic, several different types of dentine adhesion systems (Dentine Bonding Systems or DBS's) have been introduced. Delivered in three, two or one-component systems (etching, priming and bonding or combinations of these functions in a single component), they all aim to form a micro-mechanical attachment comparable to the mechanism for enamel as a substrate (Pintado and Douglas, 1988). The difference with bonding to enamel is that etching of the dentine substrate has additionally to be pre-treated. Firstly, the smear layer, the surface layer that is caused by mechanical excavation, has to be (partially) removed or modified. After removal of the smear layer, the dentine tubuli are exposed, which causes an outward flow of a water-based liquid from the pulp to the outer surface. This action not only opens multiple pathways to the pulp and thus induces potential risk for post-operative sensitivity and eventual pulpal damage, but it also makes the substrate hydrophilic (Prati et al., 1995). A major step in the bonding procedure is the priming of the dentine in order to alter the hydrophilic nature of the substrate into a hydrophobic one. Before priming, the dentine surface is acid-etched, whereby the dentine tubuli at the surface are widened and the superficial inter-tubular dentine shows an opened collagen network. Thanks to the surface conditioning, the non or lightly filled resin-adhesive can infiltrate the surface porosities of the dried dentine and subsequently set. The micro-mechanical nature of the bonding mechanism of adhesive systems to chemically conditioned dentine has well been visualized and described by scanning electron microscopy (Van Meerbeek et al., 1992). The hybridization of demineralized
dentine surface with resin tags demonstrated a substantial improvement of resin-based composite adhesion to dentinal tissues. Recently, wet dentine bonding technique (Tay, 1996) and the evolution of single step adhesive systems (Ferrari, 1997), re-directed the dentine bonding strategy in terms of more manageable clinical procedures, leading to a less operator-sensitive bonding in the dental practice.

Long term clinical durability studies (Mjor, 1997) showed that resin-based composite restorations are apart from material properties, critically influenced by the operators’ skill.

Yet the characteristics of the restorative material have to be reconsidered. Laboratory determined bond strength values of about 20-22 MPa to sound dentine are reported and appear sufficient for clinical conditions (Swift and Bayne, 1997). Recent studies, however, indicate that composite-dentine bond quality decreases with time (Hashimoto, 2000) and after mechanical fatiguing (Dietchi et al., 2001). Indeed, during clinical service, the adhesive interface is subject to considerable mechanical stress, resulting from resin-based material’s polymerization shrinkage and chewing forces developing under occlusal loading. If these stresses exceed the restoration’s bond strength to the cavity walls, debonding, leakage (Davidson and Abdalla, 1993) and premature fracture (Ausiello et al., 1999) can already occur directly after placement of the restoration or after some time when mechanical or chemical fatiguing has weakened the bond.

**Polymerization shrinkage**

The most common type of dental composite involves various types of finely ground glass powder fillers mixed into a matrix, which usually is a form of an acrylic called Bis-GMA in combination with TEGDMA (respectively Bis-GMA (2,2-bis[4-(2-hydroxy-3-methacryloyl-oxy-propoxy)-phenyl]-propane) and triethyleneglycol dimethacrylate). The
monomer will harden with the addition of a catalyst. In the case of light-cured composites, the catalyst is already mixed into the paste, but it will not become active until it is illuminated by light in a specific wavelength range (460-470 nm).

Before curing, the resin monomer molecules and the filler particles form a viscous mass, which can be squeezed into the prepared tooth cavity and shaped into the desired anatomy. Depending on the composition and the size of the monomer molecules, the conversion into the rigid phase is associated with a certain volumetric contraction. The more monomer molecules to be united into polymer chains to form rigid polymers, the higher the polymerization shrinkage. So, contraction is determined by the monomer molecule size and the degree of conversion. The degree of conversion for the high molecular weight di-acrylate monomers, which characterize most dental composite resins, is limited. This degree of conversion affects the shrinkage considerably. Employing only high molecular monomers (Bis-GMA) will affect the flow of the composite negatively. So, it is indispensable to add also low molecular weight di-acrylate monomers (TEGDMA), to control viscosity. Unluckily, an increased number of bonds to reach rigidity, will also contribute to higher polymerization shrinkage. The filler load also determines viscosity. Obviously highly filled composites show less shrinkage. In order to make the composite manageable, then, low molecular resins are admixed again, which on its turn undoes the shrinkage reduction. Different types of resin-based composites are available and characterized by inorganic filler nature, size and percentage. As the composition of the composite determines its mechanical properties, the clinical indication will be based on the composition.

The polymerization reaction, or setting process, depends greatly on the initiation of the reaction. For many years, self-curing systems were the only resin-based composites on the market to aesthetically restore decayed teeth (Lutz and Phillips, 1983). Here, the initiation
of polymerization depends on mixing benzoyl peroxide with 2% aromatic tertiary amine. Given the fact that both viscous pastes were properly mixed, a uniform polymerization throughout the whole restoration could be guaranteed. However, admixing of air bubbles could hardly be prevented, causing porosity and surface irregularities, eventually leading to discoloration. Handling was also difficult because the material mass had to be inserted and shaped before the hardening was too advanced, whilst finishing could only be started after hardening was practically complete. Yet the relatively slow setting is advantageous for the polymerization shrinkage stress relaxation (Davidson and Davidson-Kaban, 1998; Dauvillier et al., 2000).

Dentists nowadays prefer the more manageable light-curing resin-based composites. Here, reaction initiation is achieved by adding light energy to a system, where the catalyst is already mixed into the only paste. An important problem associated with light curing is the uncertainty of the quality of cure in the deeper areas of the cavity and that is due to limited light transmission. Unfortunately the sudden setting and stiffening process is always accompanied by disturbing (in many cases detrimental) stress phenomena. A variety of programmed light irradiation procedures is proposed to control the early stiffening and stress development, but it remains a paramount problem in today’s dentistry to produce an adhesive resin-based composite restoration without flaws at the marginal continuity.

The bond between restoration and cavity walls is not only challenged by the polymerization contraction, but while functioning in the oral cavity, also by alternating mechanical loading, temperature fluctuations and chemical deterioration. The quality of the restoration is greatly determined by the risk of debonding. Adhesive dentistry with shrinking restorative materials holds a contradiction. Without bonding to the cavity walls, the contractile stress related to the polymerization will lead to a more or less homogeneous isotropic contraction of the
bulk restoration and marginal gap formation and leakage will display. However, in case of bonding, the shrinkage will be directed towards opposing cavity walls and consequently the restoration will be restrained with its related problems. If the bond survives this polymerization contraction, the remaining polymerization contraction will strain the restoration partially elastically and partially plastically. These characteristics are, among other things, dependent on the composite’s conversion rate. As the conversion progress decreases with time, time plays a relevant role in the competition between the bond strengths and the polymerization contraction stress (Feilzer et al., 1989). Shrinkage is higher during the early phase of the curing when the mass is still viscous. All effort has to be made to stimulate maximally flow when shrinkage is the highest (Dauvillier et al., 2000).

Another approach for relaxation of stress is the introduction of flexibility in the system (Kemp-Scholte and Davidson, 1990a). A solution to the problem associated with the mismatch at the adhesive interface could consist of application of an adhesive layer instead of a mere adhesive interface and adding special mechanical properties to that layer. Proper understanding of the physical phenomena occurring in the adhesively restored tooth during the placement and setting of the materials and throughout its functioning is crucial. In this way the determination of the right placement procedures and material selection are detectable. Structural analyses of the integral process may offer an essential tool for the assessment and reduction of tooth fracture risks, ensuring optimal performance in selection of the restorative material combinations and material application protocols. Since stress distribution investigation of teeth, in particular after restoration, is very complicated due to the complex geometry, computerized analysis of the internal structure (finite element analysis) represents a powerful tool to visualize the problems related to shrinkage stress and to tooth cusps displacements.
Finite element analysis

Finite element analysis (FEA) consists of dividing a geometric model into a finite number of elements (bricks, tetrahedral or other). Subsequently, with mathematical functions (approximated), variables of interest are ascribed to each element or group of elements. FEA permits evaluation of the response of a system under various load or geometric conditions without the high variation, which characterizes laboratory experiments. Particularly, in biology with complex anatomies, FEA facilitates calculations of strain resulting from stressing the system.

There exist a wealth of literature on 2D FEA studies, but scientists are still pioneering in 3D FEA. Dalstra et al., (1995) successfully applied 3D FEA to obtain data by computer topography scans while studying trabecular bone density and distribution of pelvic bone zones. In this way, the complex mechanics of the pelvic bone was firstly three dimensionally modelled and analysed in order to obtain a more realistic meshed model and detailed information on its critical biomechanics in human physiology. Apicella et al., (1998) simulated with 3D FEA the effects of eccentric occlusal loading (occlusal canine guidance and posterior-anterior group functions) applied on prosthetic structures (cantilever) on the implants and at the corresponding bone-implant interface. Recently, Beek et al., (2000) used 3D FEA to investigate temporo-mandibular joint disc physiology in humans. This approach permitted the evaluation of the stress and of the strain distribution located in the intermediate zone of the articular disc. This simulation predicted the possible disc deformation for relatively small joint loads. In a second 3D FEA study conducted on cartilaginous structures in the human temporo-mandibular joint, Beek et al., (2001) revealed how the load distribution capability of the disc appears to be proportional to its elasticity and how the fibro-cartilaginous layers on the articular surfaces enhanced it. From the above-cited literature it can be
concluded that FEA offers a great potential for the study of stress and strain behaviour in teeth systems. Sakaguchi (1991) demonstrated the use of two-dimensional (2D) FEA for numerical investigation of stress distribution in teeth. Further sophistication of the geometry also enables to study 3D stress and strain distribution phenomena in teeth. This is particularly important to understand the effects of the use of ultra thin adhesive layers in combination with the diverse and complicated resin-based composite restorations, whose mechanical behaviour is so largely associated with shrinkage problems and mismatching mechanical characteristics. In fact, at the present time, a 3D FEA approach is practically the only way to obtain a meaningful image of all mechanical processes, which simultaneously take place. Wendt (1991) demonstrated that laboratory loading tests conducted on human sound and restored teeth are hard to interpret due to wide geometrical and material variations between the sample teeth and the destructive nature of the tests. An analogue numerical approach, as it is foreseen in FEA, can eliminate many of the problems mentioned before (Khera, 1991).

Occlusal loading

A variety of components are present in adhesively restored teeth, which will lead to non-uniform straining during temperature fluctuations, occlusion and mastication (McNeil, 1997). Therefore it has to be emphasized that, even if the restored tooth survived the above discussed setting shrinkage stressing, other sources would ceaselessly contribute to repeatedly dimensional changes in the adhesive resin-based composite restorations. They are concentrated at mechanical discontinuities such as those at the interface between the cavity walls and the restoration. In vitro investigations into fracture resistance of restored teeth were done by static (Wendt et al., 1987) or by dynamic
loading (Darbyshire et al., 1988). Not only because of the differences in
the method of loading, but also because of the great variety in anatomy
and mechanical properties, published fracture resistance values are
not very consistent. At present, particular interest lies in the eventual
reinforcing effects of employing adhesive techniques. The pattern of
fracture of the adhesively restored tooth is usually uniform and proceeds
adhesively or cohesively (Wendt, 1987). This is in contrast with
natural sound teeth, where the pattern of fracture is unpredictable.

Notwithstanding the absence of a reliable strength value for sound
teeth, it was demonstrated that, strength levels were obtained by
some of the adhesive systems, which did not differ significantly from
those of a natural sound tooth (Wendt, 1987; Ausiello, 1997). As
sound human premolars seldom fracture under normal conditions, it
may be expected that the optimally restored premolars will only break
at “over-functional” loading conditions.

So far the publications regarding fracture resistance were mainly
based on static loading tests. However, under clinical conditions, teeth
are repeatedly stressed by thermo-cycling and mechanical fatiguing.
To mimic reality in a more realistic way, also cyclic loading tests have
to be performed at loading forces that are far below the failure level
from the prior static experiments. Due to fatigue loading, multiple
micro-fracturing and partial separating can arise. After ceaseless
loading the micro-cracks grow and reach other cracks, thus forming
macro-cracks, leading to lose parts, substantial weakening of the
specimen and ultimately to complete failure. Obviously suchlike
samples ultimately will fail at lower forces than the un-fatigued
samples (Braem et al., 1995; McCabe et al., 2000). Bond failure will
not only reduce the strength of the restored tooth, but it will also affect
leakage, the most important cause of failure of a restored tooth
(Brännström, 1982).

Parallel to the 3D finite element analysis study of the effects of
shrinkage on the stress distribution, this method of approach can
also offer useful information about the effects of occlusal loading. A combination of both effects approaches reality best and will reveal the weakening of a pre-stressed situation on the fracture resistance of the adhesively restored tooth. The combined FEA will disclose fail-safe boundaries on the physical properties and geometrical dimensions (e.g. flexibility and thickness to maximize stress absorbency) and therefore it will be of substantial help for optimal selection of materials and placement techniques for flawless adhesive restoration with resin-based composite materials.

To avoid complicatedness from too many variables, in most published studies on this subject, compliance of tooth structure by strain was excluded. Although tooth structure is a brittle material, it will also deform elastically, be it only slightly, under loading and thus including Young’s modulus values of the materials involved in the calculations is of paramount importance when studying stress distribution. It was the aim of the present study to take into consideration the strain of the relevant structures. As many variables had to be studied simultaneously, three-dimensional finite element analysis (3D-FEA) was selected as the most practical instrument to bridge pure theoretical and experimental stress determinations. In particular, it could offer useful indications and understanding for improved selection and application of adhesive and restorative materials. This study is focused on the mechanical behaviour of a very critical case in restorative dentistry, that is a Class II MOD restoration in a first upper premolar. It was the aim of this study to investigate the possibilities of FEA to study stress distribution in premolars with deep adhesive MOD composite restorations in order to reveal conditions for fail/safe of applying dentine bonding as a means for reliable restorative dentistry. Notwithstanding the limitations of laboratory tests, validation of the FEA was studied on mechanical loading experiments on adhesively restored MOD cavities in extracted first upper premolars and literature data.