Distributed Crack Analysis of Ceramic Inlays

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In all-ceramic restorations, crack formation and propagation phenomena are of major concern, since they may result in intra-oral fracture. The objective of this study was calculation of damage in porcelain MOD inlays by utilization of a finite-element (FE) implementation of the distributed crack theory. “Damage” is defined as the parameter that describes the local decrease of stiffness caused by microdefects. In the simulated MOD ceramic inlay, the crack initiation starts at the internal occlusal surface near the pulpo-axial line angle. This initiation is invisible from the external surface and cannot be detected by the clinician. The crack initiation at the internal surface started as soon as 55-60% of the loading needed for complete fracture was reached. The use of FE techniques for calculation of the fracture in loaded ceramic inlays offers prospects for further detailed study of the crack behavior, including three-dimensional modeling and cyclic loading situations.


Introduction.

The use of ceramic inlays is becoming more popular because of increased interest in esthetics and concern about amalgam and posterior composites. Class II ceramic restorations are esthetically favorable alternatives to amalgam, and the current high-quality dental ceramics are among the most biocompatible materials to be used for dental restorations to date (Bergman, 1990).

All-ceramic materials are characterized by brittleness and relatively low tensile strength. Therefore, under clinical conditions, the fracture behavior of an all-ceramic restoration is an important feature. Banks (1990) has reviewed ceramic systems for posterior inlays and onlays, highlighting the importance of load transference and methods of attachment to tooth substance. Unsupported ceramic has very low resistance to fracture. The inclusion of voids in the cement layer or deterioration of the luting medium can lead to the onset of failure. Crack initiation and propagation occur, leading to growth of internal damage in the material and ultimately to failure of the restoration.

Crack concept.—Experimental investigations of failure of brittle materials showed the presence of a zone of microcracks which develops in the area of highest stress, the so-called ‘crack band’ (Bazant, 1986) with localization of deformation (Fig. 1). These microcracks may increase the toughness of the material and consequently reduce the risk of sudden failure. However, if growth of microcracks continues, coalescence will eventually result in a macrocrack. The ‘smear crack’ theory (Rots, 1991) was proposed to model and analyze this material degenera-

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Fig. 1 – Part of a bar under tensile loading (F): localization of deformation in the crack band.
and to use this theory for calculation of damage in porcelain MOD inlays. The evaluation is performed qualitatively, and computational results should globally describe the initiation and development of a macrocrack until fracture occurs.

Materials and methods.
In this study, finite-element (FE) calculations were performed according to the distributed-crack concept by implementation of the general-purpose FE code DIANA (De Borst et al., 1985) dealing with the constitutive relationships for brittle disintegrating material.

Model.—A plane-strain finite-element model of the central mesio-distal section through a restored premolar tooth (section thickness of 1 mm) was created by means of the software package I-DEAS (SDRC, 1986). An MOD ceramic inlay was simulated in two dimensions. The basic model geometry represented the actual dimensions (Fig. 2); the substructures dentin, enamel, and porcelain can be distinguished. The inlay was luted with resin-based cement, and a perfect bond to enamel and dentin was assumed. Besides, the cement interface layer is negligibly thin (related to the dimensions of the other constituents in the model), and therefore the enamel and dentin can be considered to be perfectly bonded to the porcelain. Symmetry was assumed with respect to the transverse plane. This results in constrained degrees of freedom (DOF) in the x-direction along the symmetry axis (y-axis). The base of the model was assumed to be fixed: The DOF of the nodes positioned on the x-axis were suppressed in the x- and y-directions. Occlusal loads were applied at the marginal ridge of the restoration in the negative y-direction.

Preliminary modeling.—To obtain insight into the mechanical behavior and stress distribution, we performed a first analysis assuming linear-elastic, homogeneous (for each substructure), and isotropic material behavior. The material properties assigned, Young's modulus (E), and Poisson's ratio (ν) are shown in Table 1. The pulpal area was assumed to be a void, with negligible contribution to the mechanical stiffness. The analysis of a model loaded at the marginal ridge (100 N) and utilizing a coarse mesh (Fig. 3) supplied information about highly stressed areas (maximum principal stresses). For this preliminary analysis, a combination of triangular and quadrilateral elements was used, sufficient to indicate the locations of the highly stressed areas, which can be regarded as predisposition sites for crack initiation. Based on these results, the mesh was refined in the critical areas: (1) the approximal incline near the load application, and (2) the occluso-axial and cervico-axial internal surfaces of the inlay (Fig. 4).

Modeling for damage calculations.—The analysis was based on the 'fixed crack' simulation technique, to be one of the possible options in the DIANA FE code (De Borst et al., 1985). With use of this code, a standard nonlinear, incremental, iterative approach was performed. The theory of this crack concept describes the deterioration of the material, characterized by the tensile strength (f'), energy release rate (G'), crack band width (w), and the shape of the stress-strain curve of the material in the crack band during softening (Bazant and Oh, 1983). Moreover, assumptions are made about the decrease of the shear resistance in a crack by means of the shear retention factor (μ). It was assumed that failure will occur only in porcelain. This assumption was verified later.

The material properties w (crack band width) and G (energy release rate) for porcelain are not readily available from the literature. In plane strain, the energy release rate can be determined from the stress intensity factor K (Kanninen and Popelar, 1985). The stress intensity factor and energy release rate used are given in Table 1. The crack band width of porcelain is unknown. Therefore, this value was estimated taking into account the average sizes of the grains and tripled in accordance with the usual empirical rules for granular materials (Bazant and Pijaudier-Cabot, 1989). For porcelain, the largest material component was considered as the 'grain', and its size was taken to approximate the value of the crack band width, 0.1 mm.

As recommended by Rots (1988), the sizes of the elements for the highly stressed locations in the porcelain substructure (Fig. 4) were taken as approximately equal to the value of the crack band width of 0.1 mm.

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The boundary conditions assigned were identical to those in the preliminary modeling. The load cases were defined as follows:

1. A single occlusal concentrated load was applied to the marginal ridge of the restoration in a vertical direction (Fig. 3).
2. A distributed load was applied over a small region of the marginal ridge (0.25 mm) in a vertical direction.
3. A distributed load was applied over a wider region of the marginal ridge (0.5 mm) in a vertical direction (Fig. 4).

Application of smeared-crack concept.—In this concept, the cracks are defined in the integration points of the elements, i.e., discrete points to compute the elemental
TABLE 1  
MATERIAL PROPERTIES OF THE VARIOUS COMPONENTS

<table>
<thead>
<tr>
<th>Property</th>
<th>Notation</th>
<th>[unit]</th>
<th>Porcelain</th>
<th>Dentin</th>
<th>Enamel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>E</td>
<td>[GPa]</td>
<td>70.01</td>
<td>18.32</td>
<td>75.01</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>ν</td>
<td>[-]</td>
<td>0.31</td>
<td>0.35</td>
<td>0.36</td>
</tr>
<tr>
<td>tensile strength</td>
<td>f_t</td>
<td>[MPa]</td>
<td>24.82</td>
<td>51.78</td>
<td>10.38</td>
</tr>
<tr>
<td>stress intensity factor</td>
<td>K_n</td>
<td>[MPa m^1/2]</td>
<td>1.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy release rate</td>
<td>G_t</td>
<td>[J m^2]</td>
<td>18.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>crack band width</td>
<td>w_c</td>
<td>[mm]</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Jones et al. (1972).  
2Craig and Peyton (1958).  
3Craig et al. (1961).  
4Anusavice et al. (1986).  
5Leone and Fairhurst (1967).  
6Bowen and Rodriguez (1962).  
8Leone and Popelar (1985).

mechanical behavior (Bathe, 1982). The crack is numerically simulated by an adjustment of the compliance matrix at the integration point level. Cracks may be modeled as: (A) fixed—the direction of the crack is constant; (B) multidi- rectional—several cracks with various directions are located at one integration point; and (C) rotational—the direction of the crack may change during the loading process. For this study, the fixed variant (A) was chosen because, from a mechanical point of view, no important changes occur in the direction of the principal stresses during the loading process. The loading process was considered as a sequence of quasi-static loading steps (increments). Initially, for small loads, the theory of linear elasticity was assumed to be applicable. Linearity was maintained until the maximum local principal stress reached the strength limit of the material, whereafter initiation of mode I cracking in the plane normal to the maximum principal stress will occur. From that moment, the local constitutive behavior was characterized by a transverse isotropic compliance matrix with isotropy in the crack plane.

The material degeneration was expressed by the softening curve and the shear retention. A linear stress-strain relationship was assumed to represent the softening behavior. In the one-dimensional case, the stress-strain curve showed the pattern depicted in Fig. 5. The elastic linear curve held up to a certain load (f_t). At this load, a crack was initiated. After initiation of a crack, the strain will increase while the stress will decrease. The cracks open and the shear stiffness along the cracks is reduced (Fig. 6). This was taken into account by incorporation of a shear retention factor β, indicating the reduction of the shear modulus after crack initiation. This characteristic quantity for porcelain is not available from the literature. According to Leibengood et al. (1986), the shear retention factor β is 0.4 for concrete. At the microstructural level, concrete and porcelain are similar; consequently, this value of β was used here. When the stresses normal to the crack are zero, the fracture is called complete. Due to the initiated cracks, the surrounding material outside the crack band width may relax along the linear elastic curve.

The energy release rate (G_t) was represented by the surface below the stress-strain curve multiplied by the crack band width. This energy release rate can be interpreted as the dissipated energy per unit surface of a completed crack. The first part of the stress-strain curve is determined by the elastic modulus (E) and the strength limit (f_t) of the material (Fig. 5). When E, f_t, G_t, and w_c are known, the second part of this curve, defined by μ (μ < 0), can be determined. The reduction factor μ is a constant which denotes the negative tangential stiffness (softening) after crack initiation at increasing strain.

Damage calculations in the MOD ceramic inlay were executed by FEA based on the input values in Table 1. The incremental nonlinear analysis offers the prospect of stepwise tracking of the propagation of the crack.

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Fig. 4—Refined mesh as used for damage calculations depicts the location and direction of the distributed load (F_2).

Fig. 5—Tension-softening curve for all material points in the porcelain. The elastic linear curve is determined by the elastic modulus (E) and the maximum strength value (f_t). The stress (σ) vs. strain (ε) relationship after initiation of the crack is determined by the reduction factor μ (μ < 0).
Results.

A selection of the resulting data is shown by some representative graphs. For small values of the load, a negligible area of crack initiation occurred externally at the proximal incline near the loading site. Thereafter, crack initiation was induced at the internal surface. This area of crack initiation was situated at the occlusal region of the internal surface of the inlay near the occlusal-axial line angle (Fig. 7a). The cracks grew, in the first instance, in the negative x-direction along the internal surface area, with a light propagation of the area toward the occlusal in the positive y-direction (Fig. 7b). Subsequently, a subarea of crack initiation originated near the internal line angle of the restoration (Fig. 7c). This process was followed by mutual approach of the various areas until a complete crack was present between the internal and external occlusal surfaces (Fig. 7d). A comparison of the internal crack patterns at various loading cases showed a striking similarity (Fig. 8 vs. Fig. 7c).

Resulting forces at the various phases of crack initiation and complete fracture are depicted in Table 2. The crack initiation at the internal surface started as soon as 55-60% of the loading needed for a complete crack was reached.

Discussion.

Modeling parameters: Plane-strain condition.—Plane-strain modeling has been utilized for simulation of the ceramic MOD inlay. The inlay is confined between the relatively stiff buccal and lingual cusps, which justifies a two-dimensional approach to the problem.

Mesh size.—Construction of a FE model starts with the division of the configuration into a mesh of discrete elements. In general, the sizes of the elements influence the results of calculations by FEA. This general rule applies especially in crack simulation studies. At the element level, the crack is distributed over the entire element; therefore, the element size near the crack site should be equal to the crack band width of the material (Bazant and Oh, 1983). A number of cracked adjacent elements constitutes the structural crack band. For the purpose of this study on ceramic inlays, the mesh size used in the porcelain met the requirements.

Load situation.—The loading cases simulated in this study represent physiological loading of the marginal ridge of an MOD restoration by the opposing cusp during mastication of food. In future studies, a variety of occlusal loadings will be included in the analyses, because the orientation of the load has an important effect on development of the stresses (Hojatie and Anusavice, 1990).

Assumption.—Failure is assumed to occur in the porcelain part only. So that this assumption could be verified, the stress patterns in the dentin and enamel substructures were evaluated. The stresses in both areas did not

![Fig. 6](image_url) - Schematic representation of the shear resistance at crack opening. Although the material shows a complete crack, the grains still give some resistance against the shear forces (arrows).

![Fig. 7](image_url) - (a) Crack initiation area at the external surface and the internal occlusal surface at a distributed load of 60 N (see arrows). The microcracks (small lines) at the integration points are shown. (b) Crack propagation shows central and occlusal extension (see arrows) of the crack area at the internal occlusal surface at 81 N (distributed load). (c) At 92 N, a sub-area of cracks (see arrow) originates near the internal line angle of the restoration (distributed load). (d) Complete crack at 112 N (distributed load).
exceed the tensile strength limits for these materials. Therefore, the application of crack theory for these materials could be omitted.

**Material parameters:**

*Crack band width.*—The crack band width of porcelain was estimated according to an empirical rule for granular materials. Because of the dependency of the mesh size on this value, it is difficult to distinguish the particular effect of this single parameter. A change of the w value necessitates a change in mesh size and consequently leads to a change in accuracy of the calculations of stress concentrations. However, at constant G, a change in w also results in a simultaneous change of the slope of the stress-strain diagram (μE). Nevertheless, the combination of these influences does not produce a magnifying effect on the outcome, but rather the influences compensate each other. Further experimental study on porcelain is required to elucidate the actual value of this material property.

*Reduction factors.*—In a granular, brittle material, the crack propagates in a capricious manner, and the two opposite crack surfaces (possibly with particles in between) will still show shear resistance after cracking. The granular roughness of the crack surface provides some shear resistance by its protruding particles. The decrease in shear resistance after cracking is expressed by the shear retention factor β, which is hard to determine experimentally, and numerical sensitivity studies should be done to reveal the influence of this parameter on the final results.

The softening curve of dental porcelain is not known, and the reduction factor μ was assumed to be a constant. The shape of the softening curve after crack initiation was assumed to be linear. The determination of the actual shape of the softening curve for dental ceramics requires sophisticated experimental research to increase the reliability of numerical simulations.

*Crack pattern.*—At the marginal ridge, the first area of crack initiation starts at relatively low loading. This crack initiation is located near the sites of application of the loads. In the immediate vicinity of the sites of load application, the numerically determined stress state may be unrealistic. For study of the behavior in this area, other refined modeling techniques (with incorporation of contact phenomena) should be applied. Therefore, this first area of crack initiation is considered to be insignificant, which is supported by the very slow extension of this area during the incremental loading process.

For the various stages of crack initiation and propagation, the associated loads are shown in Table 2. As expected, the initiation at the external occlusal surface was dependent on the load simulation. In comparison with a concentrated load application, the stress concentrations at distributed loading are lower and the material is less prone to cracking according to the distribution of the entire load over a larger area. The crack initiation at the internal surface of the inlay is present with all loading types at the same load level. The influence of the specific distribution of the load at the sites of application is negligible there, because of its longer distance from the point of load application (De St-Venant principle in continuum mechanics).

The extending crack areas approach each other. The moment of complete crack formation (the moment that the distributed cracks coalesce throughout the porcelain) varies for the three simulations. However, the differences are relatively small. The crack growth increases toward the end of the process.

This study describes loading of the inlay in a vertical direction. Studies including more severe load cases (e.g., oblique) are ongoing. When the crack forces are compared

**TABLE 2**

<table>
<thead>
<tr>
<th></th>
<th>Concentrated Load</th>
<th>Distributed Load (0.25 mm)</th>
<th>Distributed Load (0.5 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External crack initiation</td>
<td>21 N</td>
<td>22 N</td>
<td>33 N</td>
</tr>
<tr>
<td>Internal occlusal crack initiation</td>
<td>57 N</td>
<td>60 N</td>
<td>60 N</td>
</tr>
<tr>
<td>Complete crack</td>
<td>99 N</td>
<td>103 N</td>
<td>112 N</td>
</tr>
</tbody>
</table>

Fig. 8—At 92 N, the sub-area of cracks (see arrow) originates near the internal line angle of the restoration at concentrated loading.
with those developed during clinical mastication, crack initiation will not occur under the usual service conditions. This is in accordance with clinical findings that porcelain inlays fail in less ideal circumstances, e.g., heavy occlusal contacts, initial damage in the porcelain, unexpectedly biting on a stone in bread (Christensen et al., 1991). Moreover, in the clinical situation, the inlay may often be luted on top of a low-modulus base cement, resulting in a local increase in deformation when loaded.

Although the bite forces needed for complete crack development are quite high, lower level bite forces may also induce crack initiation. The internal surface of the inlay may exhibit critical flaws initially. Surface flaws will degrade the intrinsic strength of the porcelain (Anusavice et al., 1991). Presence of such flaws in the model will decrease the magnitudes of stress that are required for crack initiation. Damage to ceramics is known to be strongly influenced by a wet environment (Sherrill and O’Brien, 1974; Anusavice and Lee, 1989). This may induce crack propagation at lower load levels, followed later by complete cracking of the porcelain. The resulting crack patterns as calculated by this method depict internally-located clinical failure sites. Further clinical studies of crack patterns and fracture sites of all-ceramic restorations should be performed to provide clinical data that can be related to experimental and numerical results.

**Numerical analysis.**—The numerical approach used in this study is capable of predicting failure sites in restorations of brittle materials in areas which can hardly be detected by other methods. For these techniques to be used fully, more data are needed on the material behavior of dental porcelains. The bilinear stress-strain relationship is a simple approach to more complex behavior. Quantitative information can be obtained only if adequate material data describing the actual softening curves of dental ceramics are available. Extended experimental investigations will provide an improved material model. Studies on concrete were more reliable when a non-linear, exponential relationship between stress and strain in the crack band was implemented (Rots, 1988). Moreover, the crack band width and the shear retention factor of porcelain need to be determined experimentally. Along with this complementary research, this technique shows promise for future study of the crack behavior of ceramic restorations.

The two-dimensional modeling process (plane-strain conditions) may be extended into three-dimensional modeling. The assumption of symmetry may be changed, allowing other loading directions to be simulated and subsequently analyzed. Extended three-dimensional modeling of various restoration geometries may be considered in the future, which should take into account the fatigue behavior of the component materials.

From a theoretical point of view, appropriate modifications of the method (Pijaudier-Cabot and Bazant, 1987; De Borst and Muhlhaus, 1991) will reduce the mesh sensitivity of the numerical results. Moreover, improved constitutive modeling of the brittle behavior, combined with experimental investigations, will extend the present capabilities of the procedure.

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**REFERENCES**


