Shear stresses in the adhesive layer under porcelain veneers

A finite element method study

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Troedson M, Dérand T. Shear stresses in the adhesive layer under porcelain veneers. A finite element method study. Acta Odontol Scand 1998;56:257–262. Oslo. ISSN 0001-6357.

A finite element study was made investigating the shear stresses in the composite cement layer and the enamel bond under loaded porcelain veneers. The maximum shear stresses were calculated under various conditions concerning loading angle, laminating extension, and cervical design. The result of the study was that maximum shear stresses did not exceed the stress level for debonding, but that great differences in maximum shear stress appeared with varying loss of bond and different loading angle. The fully laminated facing showed stress levels in the composite cement only 1/5 of those in the facing with a lack of adhesion in the periphery, and 1/15 in the enamel bond. The maximum stresses increased about 4 times when the load angle was 30° as compared with 0°, and increased about 1.5 times from 30° to 60°. The importance of getting a full lamination of the veneer and avoiding unfavorable loading conditions is emphasized in this study. □ *Composite cement; enamel bond; finite element method study; shear stress; veneer*

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An important characteristic of the human face is the look of the upper front teeth. A discontinuity or a mismatch in color usually gives a negative impression of the person. The introduction of porcelain veneers in the early 1980s has caused an interest in covering discoloration, staining, and small accidental fractures with a minimum of tooth preparation and a good esthetic result. Developments were made from the original method used by Calamia (1) and Friedman (2), involving no preparation of the tooth, to a reduction corresponding to the thickness of the laminate veneer. The laboratory procedures have been described by Chalifoux & Darvish (3) and Terry (4), using either a platinum foil or a direct modeling from a special investment cast. The precision and thickness of the cement layer were examined by Wall et al. (5), and thickness was found to vary between 5 μm and 80 μm, with an average of 25 μm. Investigations in vivo concerning the long-term prognosis of laminate veneers have been conducted; the results after 3 years by Nordbø et al. (6) showed a 20% failure rate, while Christensen & Christensen (7) had no loss of veneers after the same observation period. Studies after 10 years were presented by Garber (8), who reported a failure rate of 25%. Dunne & Millar (9) suggested changes in bonding conditions together with the magnitude of applied load to be the main reasons for failure, and Wall et al. (5) considered the angle of load to be of high importance. The magnitude of stresses in porcelain veneers and in the cement layer under different loading conditions is very difficult to measure in vivo, and such measurement has never been attained.

Investigations into which part of the enamel–resin–composite–porcelain laminate the system brakes have shown that the gluing interface is the weakest part of the lamination, and that it will fail due to shear stresses. In vitro studies of the maximum shear stresses in the composite cement layer necessary to debond porcelain from enamel have been made by Lu et al. (10), and by Stacey (11) with different materials. The highest numeric value of load needed to debond porcelain from enamel was found with etched silane-treated porcelain discs bonded to etched enamel (62.5 MPa). The experimental methods involved testing adhesive materials and their physical properties, but the stress distribution under clinical load was not investigated. One way of achieving this in vitro is by using the finite element method (FEM), which has been widely used in several dental reports. The method used here has been described previously (12). The aim of this study was to calculate the shear stress in the composite cement and the enamel bond with the facing loaded in the incisal area under different angles and adhesive conditions.

Materials and methods

Two-dimensional finite element models of veneers on teeth with an intermediate layer of resin were designed according to the size of an average upper central incisor. The abutment tooth was considered to be homogenous, and the remaining enamel layer under the buccal surface of the veneer and the pulp were treated as dentin with regard to material properties. The study was made using a Hewlett-Packard computer (9000/720) and the ABAQUS FEM program, which was appropriate for this study (Hibbit, Karlson and Soerensen, Pawtucket, R.I., USA). Three models of the tooth were created with different

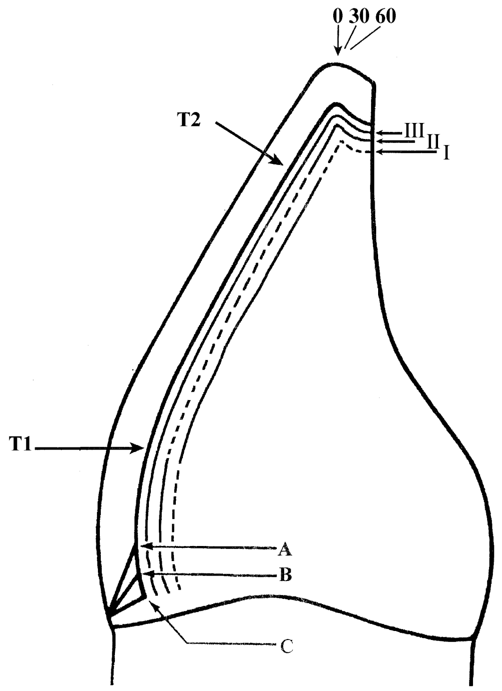

Fig. 1. The different designs and laminations. The variations in cervical design are shown by A, B, and C, and the extensions of the adhesive layer are marked I, II, and III. Loading points are at the incisal edge at the various angles. T1 and T2 are the points where the adhesive layer ends for gluing types 1 and 2.

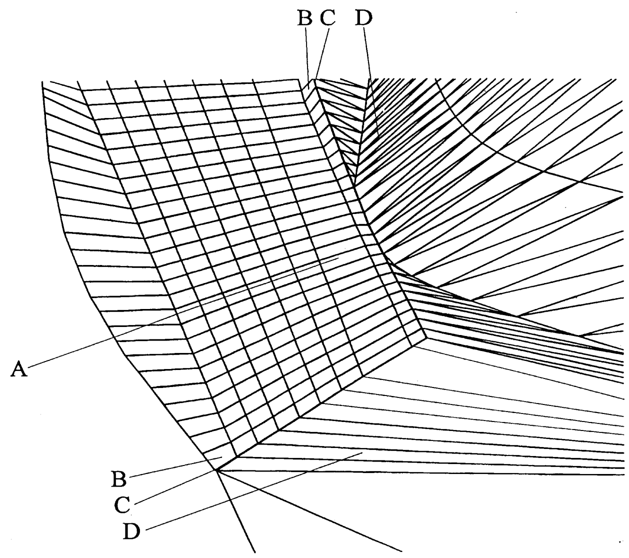

Fig. 2. Enlargement of the finite element mesh, showing the porcelain layer, A, consisting of eight layers of elements. The composite cement layer, B (25 μm), has one element layer. The tooth, D, is in three-node elements. Not visible in this magnification is the layer of bonding resin, C (5 μm), between the tooth and the composite cement.

cervical design: A, featheredge preparation; B, chamfer preparation; and C, shoulder preparation. All preparations covered the incisal edge (Fig. 1). The porcelain facings were made to be 0.5 mm thick; the composite cement layer, 25 μm; and the enamel bond layer, 1 μm. Three different adhesive conditions were tested: type 1, lack of polymerization in the periphery of the facing; type 2, lack of polymerization in the middle; and type 3, a total bonding of the facing. All models were loaded at 0°, 30°, and 60° to the long axis of the tooth. Altogether, 27 different examinations were made. A registration of shear stress in the composite cement and enamel bond was made. The models had between 8957 and 9140 elements, and between 7230 and 7290 nodes, depending on the cervical design. Four node elements were used in the porcelain and bonding layers, while three node elements were used in the tooth structure (Fig. 2) (type CPS 4 and CPS 3 in the ABAQUS program). The enamel bond and the composite cement layer had 496 elements each (Fig. 3); the porcelain layer contained 3968 elements. The registrations were made at all nodes in the composite cement and the enamel bond (in Table 2, Bond and Comp, respectively), but only the highest numeric values of maximum shear stress are revised in the table. The elements in the models were all attached, and none could move freely; even the cases with no bond were modeled as

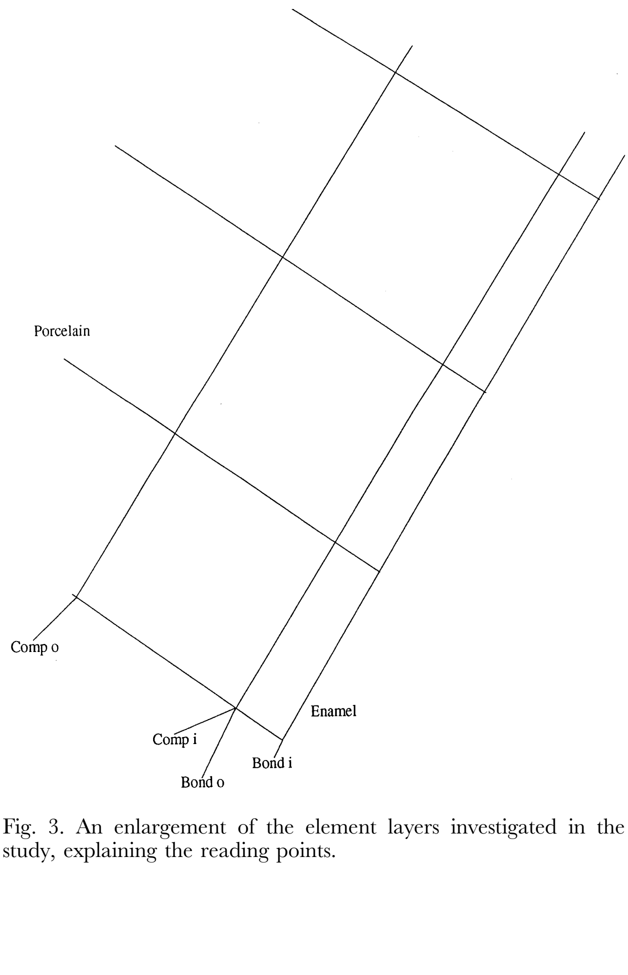

Fig. 3. An enlargement of the element layers investigated in the study, explaining the reading points.

Table 1. E-modulus and Poisson's ratio for the materials used

Material	Modulus of elasticity (GPa)	Poisson's ratio
Porcelain	70	0.14
Enamel	84	0.33
Composite cement	6	0.24
Enamel resin	5	0.40
Dentin	19	0.31

elements in order to prevent elements from passing one another under load.

The chosen program implied the following assumptions of the mechanical properties of the structures: 1) homogeneity throughout the entire structure, 2) isotropy, and 3) linear elasticity. The assumptions of homogeneity and isotropy are simplifications—ideal material modeling used to justify the use of the material properties given in Table 1 in all elements with the same material definition. In the FEM method the mechanical properties must be defined, and the values used are given in Table 1. The chosen magnitude of the load was 250 N (13).

Results

Shear stresses in the enamel bond and composite layers are given in Table 2. None of the values were located closer than 1.5 mm from the loading point, thereby reducing the influence of distortion in the loading area.

Shear stresses in the enamel bond

Maximum shear stresses in the enamel bond layer appeared when there was a lack of adhesion in the periphery and the veneers were loaded at 0° (Table 2, columns A1-0, B1-0, C1-0 Bond). In the model with a lack of adhesion in the periphery of the facing, the shear stresses were more than 1.5 times higher than any other comparable reading for the other gluing types (Table 2, A1-0, B1-0, C1-0 Bond, compared with A2-0, B2-0, C2-0 Bond and A3-0, B3-0, C3-0 Bond). Stress distribution in the enamel bond layer along the surface of the tooth with a chamfer preparation and adhesion in the middle (type 1) under the used loading conditions are shown in Fig. 4. Positive values in the figures are shear stresses in the direction from the origin in the coordinate system used; negative values are directed toward the origin (coordinate system is shown in Fig. 1). Note the peaks in shear stresses at the end of the adhesive layer for the 30° and 60° loading directions with this type of adhesion (Fig. 1, point T1). The maximum shear stress was located at the lower end of adhesion, but with only a small difference between the upper and the lower end of adhesion when loaded at 60°. Shear stresses in the bond layer increased with the angle of the load for all types of veneers except for adhesion type 1 (lack of adhesion in the periphery) with a 0° inclination of load.

Shear stresses in the composite cement

In the composite cement layer maximum shear stress also appeared when the load angle was 0° (Table 2, A1-0, B1-0, C1-0 Comp) and was about 12 times higher in this adhesion type than in the other two gluing types under the same load angle. The maximum shear stresses in the model with full adhesion were located at the cervical end of the veneers, except for the chamfer and shoulder preparations loaded at 0°, but also in these cases with a peak close to maximum in the cervical end (Fig. 5). The difference between maximum shear stress in the composite cement layer and the variation in the enamel bond layer showed a considerably higher shear stress level in the bond when the veneer lacked adhesion in the periphery. Notable also was the maximum shear stress in the enamel bond and composite cement layers with gluing types 2 and 3 under the load angles 30° and 60° (Table 2, A2-1 compared with

Table 2. Shear stresses in the composite cement and enamel bond (kPa)

	A1-0	B1-0	C1-0	A2-0	B2-0	C2-0	A3-0	B3-0	C3-0
Bond	3090	3138	3138	305	288	286	140	153	140
Comp	1578	1604	1604	134	135	133	133	132	132
	A1-1	B1-1	C1-1	A2-1	B2-1	C2-1	A3-1	B3-1	C3-1
Bond	1432	1361	1327	465	703	575	439	688	567
Comp	340	347	347	438	589	320	429	575	315
	A1-2	B1-2	C1-2	A2-2	B2-2	C2-2	A3-2	B3-2	C3-2
Bond	2098	2082	2082	676	1057	870	664	1038	861
Comp	1117	1127	1127	658	886	483	647	870	477

A = featheredge preparation; B = chamfer preparation; C = shoulder preparation.
First digit: 1 = adhesion in the middle part of the veneer; 2 = adhesion at the ends of the veneer; 3 = full adhesion. Second digit: 0 = loading angle of 0°; 1 = 30°; 2 = 60°.
Bond = maximum shear stresses in the enamel bond; Comp = maximum shear stresses in the composite cement.

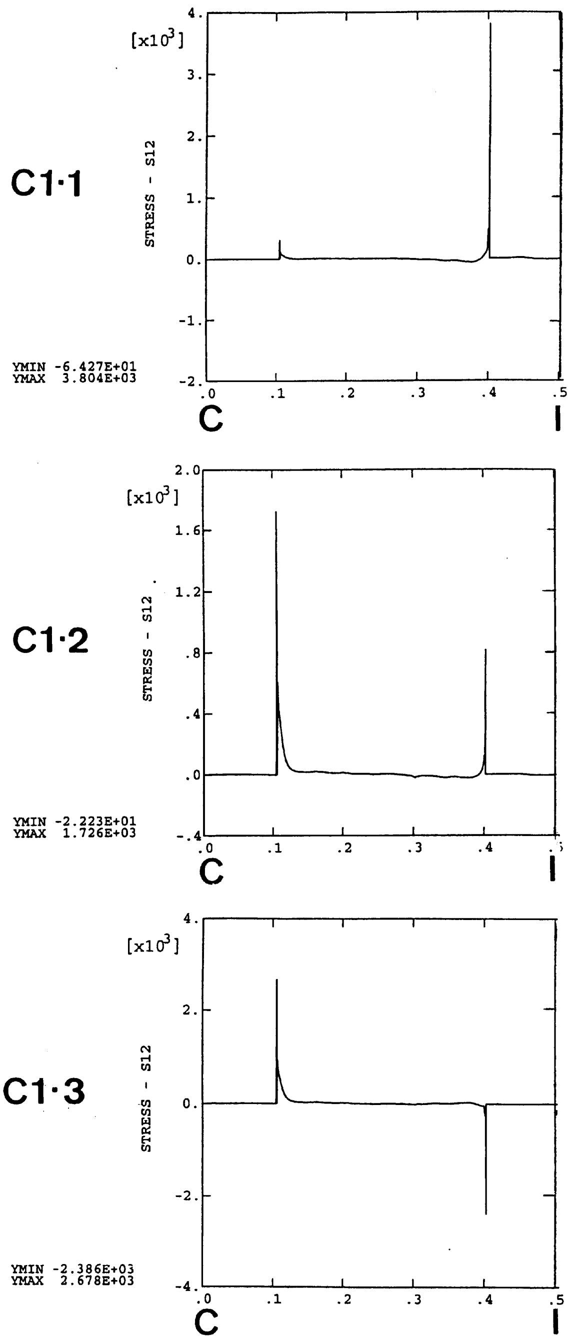

Fig. 4. Shear stress distribution in the enamel bond loaded at 0° (upper), 30° (middle), and 60° (lower) for type C facings with lamination type 1, with a lack of adhesion in the periphery. The stress distributions for all preparation cases with this adhesion type were very similar.

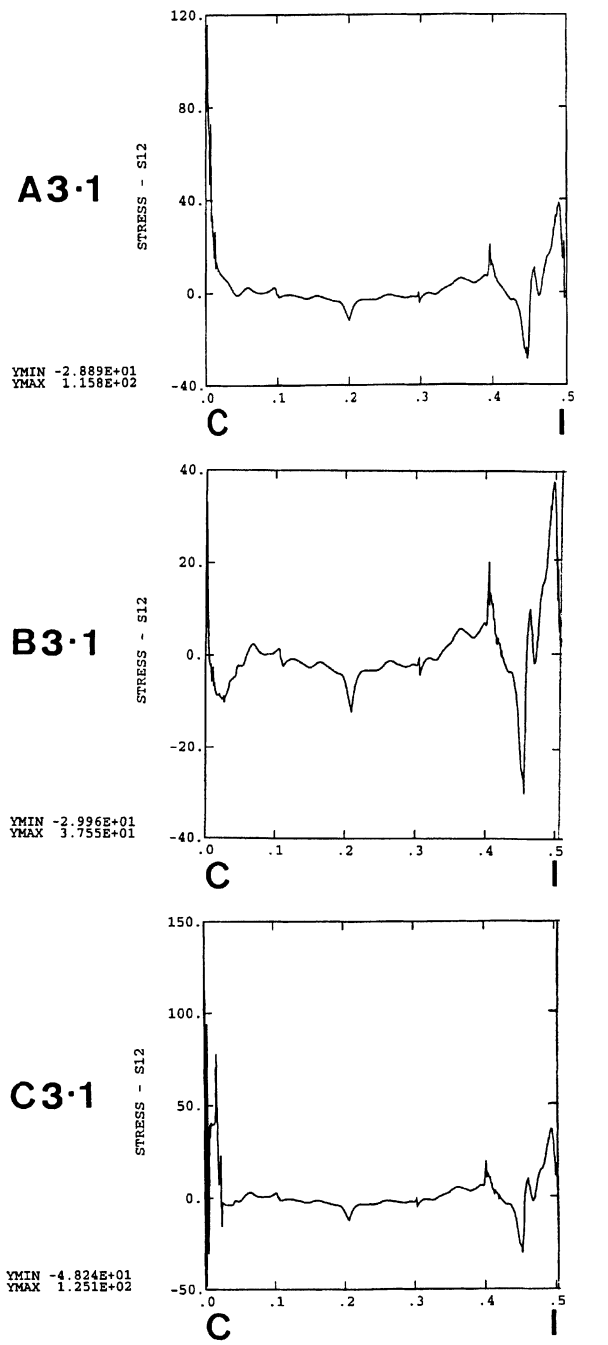

Fig. 5. A comparison of the shear stresses in the resin bond layer of fully laminated veneers (type 3) loaded at 0°. Notice the variation in maximum shear stress, which appears close to the cervical end of the facing between the different shapes, while the distribution of the stresses are rather equal.

B2-1 and C2-1; A3-1 compared with B3-1 and C3-1; A2-2 compared with B2-2 and C2-2; A3-2 compared with B3-2 and C3-2). The maximum shear stresses in these cases were about one-third higher for the chamfer preparation than the other two preparation types. For the 0° case (Table 2, A2-0, compared with B2-0 and C2-0; B3-0, compared with A3-0 and C3-0) no significant difference occurred between the preparation types. In the composite cement the values were somewhat lower for the shoulder preparation compared with other two. In the case with a

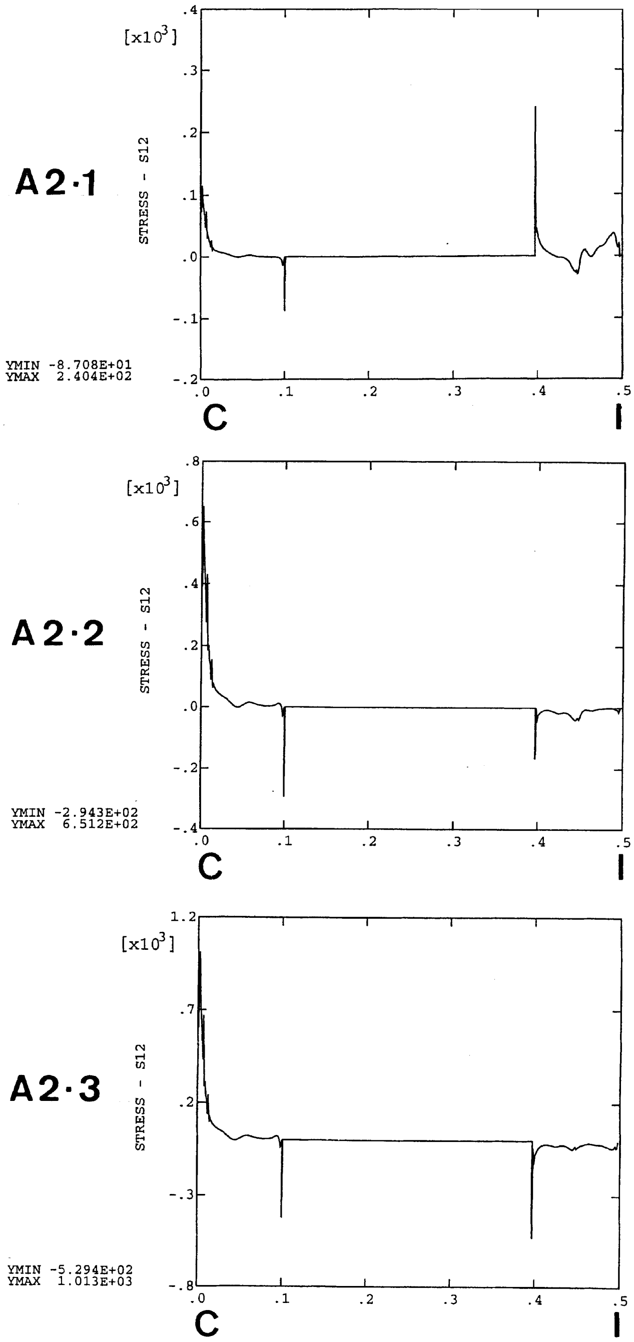

Fig. 6. A comparison of shear stress distribution in the enamel bond layer of veneer type A with the different loading conditions, laminated at the ends (type 2). Major stress for the angulated cases appears at the cervical part of the facing.

lack of adhesion in the middle, maximum shear stress for the 0° case appeared at the upper-end limit of the adhesion, while for the 30° and 60° cases the highest values were found at the cervical end of the adhesive layer (Fig. 6).

Discussion

This study was made to calculate the maximum shear stresses in the composite cement and the enamel bond under porcelain facings, under the influence of various cervical designs and loading conditions. Three different models were used to calculate shear stresses when the adhesive conditions were optimal and the influence of various weaknesses in the bonding layer that may occur with laminate veneers. Rather extensive areas of no bond were chosen to see the variations in shear stress. The findings in this study indicate that a loss of adhesion in the periphery of a veneer is critical to the construction. In all cases where this occurred, the maximum shear stresses increased between 2 and 25 times compared with the other two types of adhesion (type 1 compared with types 2 and 3). The highest stress levels were found with facings lacking adhesion in the periphery and loaded at 0°. The chosen loading point was close to the incisal edge of the tooth; the stresses for adhesion type 1 at 0° were transferred mainly along the veneer; and the shear stresses, except for deformation in the upper part of the facing, were concentrated at the upper gluing point. The difference in the magnitude of the stresses between a fully laminated facing and a facing with a lack of adhesion in the middle was minor. The conclusion drawn from this is that it is of vital importance to the veneer to have a loading point that allows the stresses to be transferred to the tooth. This means that the loading point should be attached to the tooth. The geometry applicable in type 1, on the other hand, allows the veneer to distort along the tooth.

A facing with a shoulder preparation showed a concentration of shear stresses at the cervical end for the adhesion type 2 and type 3 cases, under all loading conditions, and with a maximum at this point when loaded at 0°. According to Stacey (11) the mean shear stress needed to debond etched and silane-treated porcelain from etched enamel is 62.5 MPa. The highest value found in the present study, 3.1 MPa, was with a facing with a chamfer or a shoulder preparation type 1 loaded at 0° (Table 2, B1-0 or C1-0 Bond). In the case with a lack of adhesion in the periphery, a concentration of stresses around the end points of gluing appears, and between these points the stresses are, of course, zero. Considering the high magnitude of stress concentrated at a point, there is a risk that the enamel bond can break, owing to fatigue after some time, as it is the weakest link in the laminating chain. The preparation with lack of adhesion in the middle also showed a concentration of shear stresses in the points between gluing and no adhesion, but the magnitude of the stresses were lower; stresses were distributed along the gluing interface, and with the highest numeric values for shear stress at the same points as a fully laminated veneer. The fully laminated facing showed a shear stress concentration at the cervical margin of the veneer for all cases, with varying magnitudes for the different loading conditions. The differences between the preparation types were minor compared with the other two variables investigated. The magnitude of the shear stresses increased with the angle of loading, and the area in which they were distributed decreased. In a clinical situation where the incisal edge is loaded in an unfavorable direction during mastication, there is a failure risk due to overload. The importance of a complete lamination must be emphasized. This may be achieved by keeping the operation field dry and by using a good veneering technique. The mechanical properties of a dentin bond were not considered, but such a bond is expected to be weaker than the enamel bond, thereby increasing the failure risk. The varying rate of success reported by different investigators may be attributed to the case selection or the type of preparations used. The conclusion of this study is that a porcelain veneer that is kept inside the enamel, with a full lamination, shows fairly low shear stresses in the enamel bond and composite cement and should thus have a good long-term prognosis.

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Received for publication 25 September 1997
Accepted 9 June 1998