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In Vitro Exploration and Finite Element Analysis of Failure Mechanisms of Resin-Bonded Fixed Partial Dentures

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Abstract

Purpose: The purpose of this study was to explore the debonding mechanisms of two-unit cantilevered and straight and bent three-unit fixed-fixed resin-bonded fixed partial dentures (RBFPDs) and to measure the failure loads needed for debonding.

Materials and Methods: Failure load tests were performed using Bondiloy beams simulating both cantilevered and fixed-fixed RBFPDs, luted onto flat-ground buccal surfaces of bovine teeth with RelyX ARC, Panavia F2.0, and UniFix resin cements. The failure loads were recorded, and the debonded surfaces of both the enamel and the restorations were examined for details of interest. Finite element analysis (FEA) was used to calculate the stress concentrations within the cement layers at failure.

Results: Simulated two-unit cantilevered and straight three-unit fixed-fixed RBFPDs showed a significantly higher failure load than the simulated three-unit fixed-fixed RBFPDs with a curved appearance. The FEA models revealed the magnitude and stress locations within the cement layer, resulting in an explanation of the different failure modes.

Conclusions: The low failure loads for the three-unit bent fixed-fixed RPFPDs, compared with their straight counterparts and the two-unit cantilevered RBFPDs, indicate that clinically a reserved attitude needs to be maintained with regard to three-unit fixed-fixed RBFPDs spanning a clearly curved part of the dental arch. The FEA results make it clear which part of the tooth restoration interface is subject to the highest stress levels, making it possible to design abutment preparations that avoid high interfacial stresses to help prevent debonding.

Debonding of resin-bonded fixed partial dentures (RBFPDs) has been a problem since the early days of application.[1–5] Studies on the long-term survival of these restorations[1,2,5–8] have concentrated more on the debond rates than on the debond reasons. Clinical longevity increased significantly when grooves, guide planes, a 180° wraparound, and a chamfer were applied.[4,6,7,9,10] The influence of surface pretreatment of the restoration and the luting cement has been studied[11–13] with contradictory results, not leading to conclusive recommendations. Some authors agree that stresses in the tooth–restoration interface, that is, the cement layer, induced by mastication forces are responsible for cement degradation and subsequently for debonding.[6,14–17] Because there are essential differences between FPDs and RBFPDs, these stresses work differently between the two types of restorations. An FPD in its most elementary shape is a solid three-unit restoration cast in one piece, consisting of two abutment crowns connected by a pontic in the middle with the abutment crowns completely enclosing the abutment teeth. In contrast, the preparation of a fixed-fixed RBFPD is usually situated on the lingual or palatal surfaces. So, both abutment teeth are only partially covered by the restoration. Without a retentive preparation with occlusal support, the abutment-restoration interface, that is, the luting cement layer, has to bear the burden of the mastication forces.[18] Occlusal loading of a fixed-fixed RBFPD will in principle result in shear stress, and therefore is more susceptible to failure than a three-unit FPD with crown abutments where mainly compressive stress is induced in the cement layer.[19]

Beside the different stresses involved in the failure of RBFPDs, geometry can play an important role. The fundamental difference between posterior and anterior fixed-fixed RBFPDs is that the posterior ones usually are straight constructions, while their anterior counterparts follow the curvature of the dental arch and therefore have a curved appearance. This has consequences for the direction in which the stresses occur within the cement layers of the respective abutment teeth.

Results of clinical research into the influence of the location of three-unit fixed-fixed RBFPDs on longevity (anterior vs. posterior, mandible vs. maxilla) differ from study to study[4,7,8,20] and are sometimes conflicting, so no conclusive judgment can be drawn. Interestingly, a significantly longer clinical survival of two-unit cantilevered RBFPDs over three-unit fixed-fixed RBFPDs has been reported.[6,21] Chai et al[21] found a 48-month survival rate of 81% for two-unit cantilevered RBFPDs, which surpassed that of the three-unit RBFPDs (63%) in the same study.

Simulating a fixed-fixed RBFPD is not a simple matter. To mimic the clinically occurring interfacial stresses of fixed-fixed RBFPDs, it is not necessary to simulate in a laboratory setup an identical fixed-fixed design. When in a clinical situation one abutment tooth of a fixed-fixed RBFPD is subjected to occlusal loading, a limited axial movement of this abutment tooth will occur, creating physiological counteracting forces in its socket. However, on the other abutment tooth, relatively high interfacial torque/peel stresses may develop. As these torque/peel stresses were the main subject of our study, we chose a laboratory design in which only one abutment tooth is involved, and the counteracting forces are assumed not to be of relevance. This resulted in a straightforward test setup simulating the abutment prone to the highest interfacial torque/peel stresses. The obtained failure loads were used in finite element analysis (FEA) models to clarify differences in debonding mechanisms of two-unit cantilevered and three-unit fixed-fixed RBFPDs and the effect of the geometry.

The purpose of the present in vitro study was to elucidate why the survival rate of two-unit cantilevered RBFPDs is reportedly higher than for the three-unit fixed-fixed RBFPDs.[6,21] Furthermore, the effect of the geometry, that is, curvature of the dental arch, and the effect of the luting cement were evaluated. To study the behavior of the cement layer and the stresses occurring within, retentive preparations were deliberately omitted. Laboratory models representing the two-unit cantilevered RBFPDs and three-unit fixed-fixed RBFPDs, both straight and with a curved appearance, were prepared, and the effect of the geometry on the failure load was measured.

Materials and methods

Specimen preparation and testing

In this study, tensile peel and torque strengths of three resin luting cements in three simulated clinical situations (two-unit cantilevered RBFPDs, straight three-unit fixed-fixed RBFPDs, and three-unit fixed-fixed RBFPDs with the two abutments not in a straight line due to the curvature of the dental arch) (Fig 1) were evaluated. Cast CoCr beams (Bondiloy; Austenal, Inc., Chicago, IL) simulating RBFPDs of different size and shape were used: (i) 24 total tests with straight CoCr beams ($7.0 \times 22.0 \times 0.55\,\text{mm}^3$) simulating three-unit straight fixed-fixed (SFF) RBFPDs (group SFF), eight tests with each of the three cements used, (ii) another 24 tests with bent CoCr beams ($7.0 \times 22.0 \times 0.55\,\text{mm}^3$) with the bend (135° representing the average angle between the palatal surfaces of the upper central incisor and canine) dividing the beam in two parts ($7.0 \times 7.0 \times 0.55\,\text{mm}^3$ and $7.0 \times 15.0 \times 0.55\,\text{mm}^3$), representing bent fixed-fixed (BFF) RBFPDs (group BFF), again eight tests per cement used, and finally (iii) test results obtained in earlier research with CoCr beams ($7.0 \times 15.0 \times 0.55\,\text{mm}^3$), luted to bovine teeth[11] simulating two-unit cantilevered RBFPDs (group CAN), were used for comparative reasons. All tests (CAN, SFF, BFF) were conducted by the same group of researchers in the same laboratory.

For all tests, freshly extracted bovine teeth with flat-ground (600 grit) buccal surfaces with no dentin exposed were used. The teeth were mounted with PMMA in round copper tubes (20.0-mm long × 15.0-mm diameter) to facilitate the testing procedure. Prior to cementation, the luting surfaces of all beams were sandblasted with 50 μm Al_2O_3 particles (Korox 50; Bego, Bremen, Germany) in a Vaniman Sand Storm sandblaster (Vaniman, Fallbrook, CA) under 0.3 MPa pressure for 15 seconds. Three resin luting cements were used: RelyX ARC (3M Dental Products, St. Paul, MN), Panavia F2.0 (Kuraray Medical, Okayama, Japan), and UniFix (Cavex Holland BV, Haarlem, The Netherlands), the latter also known as Super-Bond C&B (Sun Medical Co., Shiga, Japan). Of all Bondiloy beams, an area of $7.0 \times 7.0\,\text{mm}^2$, comparable to the available bonding

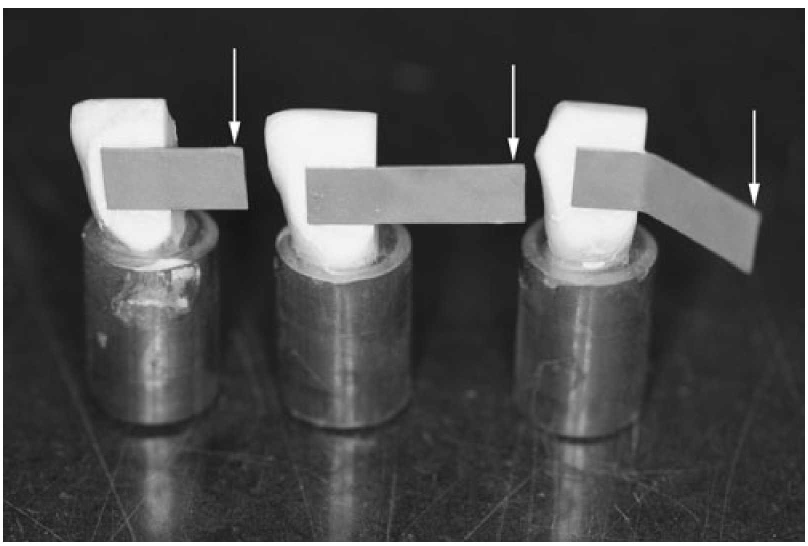

Figure 1 The different specimens as tested from left to right; CAN (simulating short straight CANtilevers), SFF (simulating straight fixed-fixed RBFPDs), and BFF (simulating bent fixed-fixed RBFPDs), with arrows indicating the direction and location of the applied load.

Table 1 Material parameters used in finite element analysis

Material	Elastic modulus (GPa)	Poisson's ratio
Enamel	84	0.33
CoCr alloy	218	0.33
Panavia	12	0.33

area on the palatal surfaces of an upper incisor or canine, was luted to the enamel surface of a bovine tooth according to the manufacturer's instructions, immediately followed by application of a standardized pressure of 50 N for 1 minute. After this minute, the pressure was released, and the edges of both the RelyX ARC and Panavia specimens were light cured according to the manufacturer's instructions. UniFix is a chemical curing luting cement not requiring light to cure. Subsequently all specimens were stored in tap water at 37°C for 72 hours prior to testing. Load to failure was applied to the free end tip of the beam (as indicated with arrows in Fig 1), parallel to its bonded surface and perpendicular to its long axis in a universal testing machine (Instron, Ltd., Wycombe, UK), using a crosshead speed of 1.0 mm/min. The load on the beam until failure was recorded. After failure, the bonding areas of both the beams and the teeth were examined under a light microscope (7.5× magnification) to estimate the percentage surface area covered with cement and for further details of interest.

Finite element analysis

Three-dimensional simplified FEA models of the three RBFPD types (CAN, SFF, BFF) were created. The finite element modeling was carried out with FEMAP software (FEMAP 8.10; ESP, Maryland Heights, MO), while the analysis was carried out with CAEFEM 7.3 (CAC, West Hills, CA). The dimensions of the enamel block representing an abutment tooth were 8.5-mm long, 10.0-mm wide, and 1.5-mm high. The cement layer was 7.0-mm long, 7.0-mm wide, and 40-μm high. The beam dimensions were described above. The models were composed of 16,800 to 19,200 parabolic hexagonal solid elements. The material properties[22,23] (Table 1) were assumed to be isotropic-homogenous and linear-elastic. The nodes at the bottom of the enamel were fixed (no translation or rotation in any direction). The mean failure load as obtained from the experimental data was applied at the points indicated with arrows in Figures 2 and 3. Two stresses were calculated: the solid major principal stress and the solid S_z stress to establish the tensile stress in the cement layer. Only the tensile stresses in the cement layer are shown in Figures 2 and 3; the compressive stresses were omitted for clarity.

Statistical analysis

Two-way analysis of variance (ANOVA) and Tukey post hoc tests were used to test the effect of the test method and luting cement on the observed failure loads. The failure mode distributions were statistically analyzed with Kruskal–Wallis one-way ANOVA on ranks. Multiple comparisons were done with Dunn's test. Statistical significance was set in advance at the 0.05 probability level. All statistical analyses were performed with SigmaStat Version 3.0 (SPSS, Inc., Chicago, IL).

Results

The mean failure loads (N) depending on the beam type and luting cement are graphically depicted in Figure 4. Two-way ANOVA showed significant difference for the beam type ($F = 356.6$; $p < 0.001$), luting cement ($F = 94.8$; $p < 0.001$), and their interaction ($F = 16.4$; $p < 0.001$). The mean failure loads and the results of this statistical analysis are summarized in Table 2. With the exception of RelyX ARC, the CAN group required a significantly higher load to debond than the SFF and BFF groups. All BFF in the laboratory tests debonded at a significantly lower failure load than SFF (Table 2, Fig 4).

The failure mode analysis was performed for the test methods and the cements, both for the enamel and Bondiloy side. The percentage of cement-covered surface area and the results of the statistical analysis are summarized in Table 3. The mean percentages of cement-covered areas on the teeth after failure do not show any significant differences, with an almost 100% mean coverage overall. On the Bondiloy side, however, the percentages of cement-covered areas vary between 6% and 100% (Table 3). This means that all cement failures are at least both partially cohesive and partially adhesive. Examining the luted metal surfaces of the BFF beams after failure also reveals that all Panavia-luted ($n = 8$) and UniFix-luted ($n = 8$) beams show a typical failure pattern, Panavia more explicitly than UniFix, as shown in Figure 5. The BFF beams luted with RelyX ARC did not show this pattern. In contrast with BFF, the luted surfaces of both the CAN and SFF groups did not show a specific debond pattern.

The mean failure loads obtained in this study and those obtained similarly before[11] were used in the FEA models (Figs 2 and 3). The different stress patterns in the cement layer due to the type of load applied are also shown. The maximum observed solid major principal stress and the solid S_z stress for the different calculated situations are summarized in Table 4.

Applying a peeling force (Fig 2A, D), resulted mainly in tensile stress ($S_z = 55$ MPa) near the enamel-pontic-transition (EPT) line. In contrast, if the force was applied from the opposite direction, that is, load (Fig 2B, E), compressive stress was observed near the EPT line, which was omitted for clarity. Approximately 1 mm from the EPT line, an area with mainly tensile stress ($S_z = 63$ MPa) was observed. Applying torque (Fig 2C, F) resulted in little tensile stress (13 MPa), but the major principal stress in the cement layer was 122 MPa. A similar stress pattern with maximum stress values was observed for SFF (Fig 3A–C). A remarkable difference in load and stress pattern is observed with BFF (Fig 3D–F). Applying a torque load of only 27 N on BFF, compared to 185 N with SFF, resulted in tensile stress (S_z) of 74 MPa in one corner near the EPT line. Besides the striking difference between failure loads of BFF and SFF, the accompanying displacement of the tip of the beam differed by almost an order of magnitude, with 17 and 104 μm, respectively (FEA calculation).

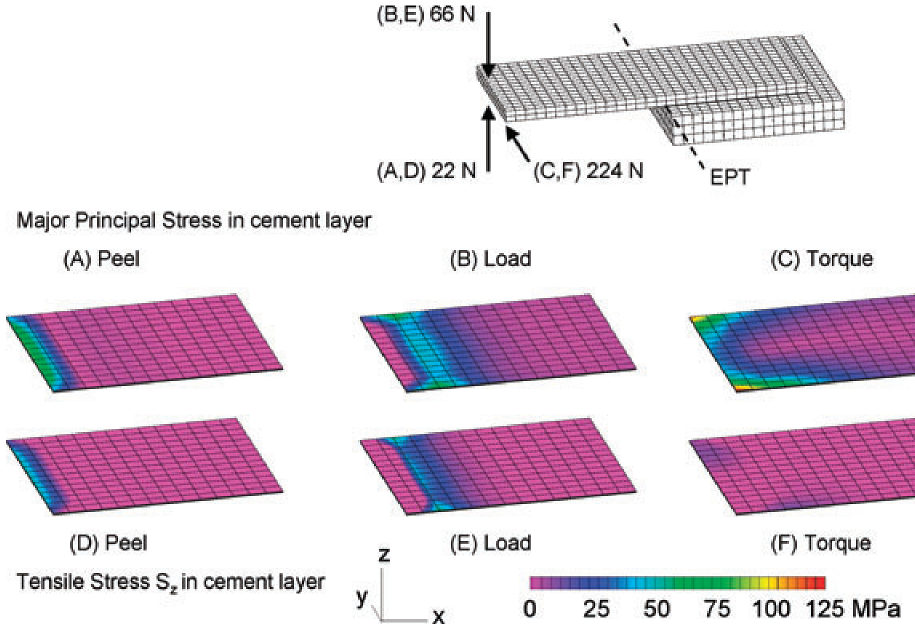

Figure 2 FEA models for group CAN (short straight cantilevers) with mean failure loads (N) from experimental tests and major principal stress patterns (A–C) and solid S_z stress patterns (D–F) in Panavia cement layers.

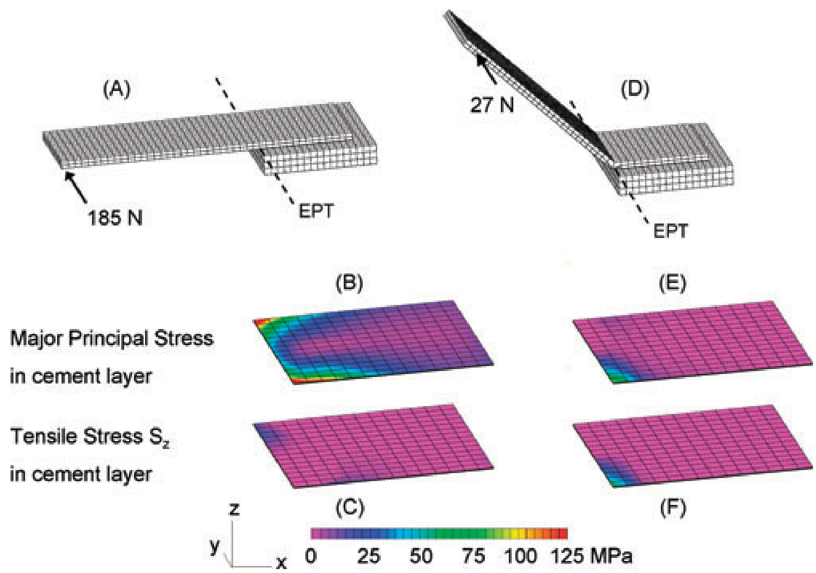

Figure 3 FEA models for (A) groups SFF (straight fixed-fixed RBFPDs; and (D) BFF (bent straight cantilevers) with mean failure loads (N) and major principal stress patterns (B, E) and solid S_z stress patterns (C, F) in Panavia cement layers.

Discussion

Debonding seems to be an inevitable consequence with RBFPDs and remains unpleasant and unwanted at any time. To understand the failure mechanisms as such within the tooth–restoration interfaces of both fixed-fixed and cantilevered RBFPDs, three test modalities were used in this study (Figs 2 and 3) without a retentive preparation to avoid preparation influences. A simulation of cantilevered RBFPDs in a laboratory setup was studied previously.[11,24,25] Behr et al[18] have compared failure rates of three-unit fixed-fixed RBFPDs in vivo and in vitro with loads applied on the pontic with significantly higher failure rates for nonretentive anterior RBFPDs. el-Mowafy et al[26] did the same in their FEA study, and a separation force between 361 and 562 N, depending on the design, was found. Both studies proved that loading the pontic of a posterior three-unit fixed-fixed RBFPD is a favorable situation, because the forces are divided over two abutments, which halves the stress in the tooth–restoration interfaces on each of the abutment teeth. Applying the same load, however, on one abutment only results in higher local stresses in the tooth–restoration interface, due to the fact that the moment is doubled compared to loading the

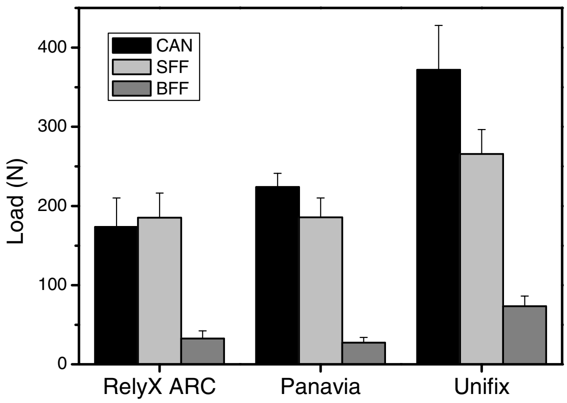

Figure 4 Mean failure loads (N) depending on the beam type [CAN (short straight CANtilevers), SFF (straight fixed-fixed), and BFF (bent fixed-fixed)] and luting cement.

pontic. An FEA study of Aydin and Tekkaya[27] showed that the stress levels in the tooth–restoration interface in a three-unit FPD were higher for loading each of the abutments instead of the pontic. So loading one abutment only, inducing higher local stresses in the tooth–restoration interface, is a better representation of the clinical situation. This resembles the long beams, both straight and bent, that were used in this study to simulate the corresponding fixed-fixed RBFPDs.

The present study used a constant thickness and only one CoCr alloy. In their FEA study of fixed-fixed RBFPDs, Sato et al[28] simulated various alloys and loaded the pontic. They varied the thickness and with that the rigidity of the RBFPD, and concluded that, irrespective of the alloy used, interfacial stress diminished with increased retainer thickness.

Table 2 Mean failure loads (N) with SD in parentheses of different luting cements depending on test type

Luting cement	CAN	SFF	BFF
RelyX ARC	173.5 (36.5)^{A}	185.1 (31.3)^{Aa}	32.7 (9.6)^{Bb}
Panavia 2.0	224.0 (17.1)^{A}	185.7 (24.3)^{Ba}	27.3 (6.7)^{Cb}
UniFix	371.9 (55.9)^{A}	265.7 (30.8)^{B}	73.4 (12.7)^{C}

Identical uppercase letters indicate no significant difference in failure load values between the test types.
Identical lowercase letters indicate no significant difference in failure load values between the different luting cements.

The results of this study offer an insight into the debonding mechanism of simulated RBFPDs. A previous study[11] of two-unit cantilevered RBFPDs showed that the torque forces required for debonding are higher (224 N) than the required load (66 N) and peel (22 N) forces. For debonding of the simulated two-unit cantilevered RBFPDs, a torque force 10 times higher than the peeling force was required. The FEA analysis (Fig 2) revealed different stress patterns within the cement layer between the different failure loads. Peel and load forces resulted in solid S_z stresses of 55 and 63 MPa (Fig 2D, E), respectively. These values are close to the Panavia–CoCr adhesive bond strength of 48 MPa reported by Kern and Thompson.[29] In contrast, the torque test revealed only a solid S_z stress of 13 MPa in the cement layer, which is too low to cause adhesive failure, but the observed solid major principal stress of 122 MPa (Fig 2C) exceeds the cohesive strength of 113 MPa of the cement, giving rise to cohesive failure of the cement layer.[30] Earlier reported cement failures[11] of similar experiments are ambiguous, and the origin of failure was not reported, so no further conclusions can be drawn. Interestingly, the adhesive bond strength of Panavia–CoCr (48 MPa) exceeds the adhesive bond strength of Panavia–dentin and Panavia–enamel of 17.5 and 35.4 MPa, respectively, while the failure is always on the cement–CoCr interface.[29] This implies that the strain in a relatively thin CoCr beam is apparently higher due to deflection of the material than in the more bulky and rigid tooth structure.

The stress patterns as shown in the peel and load situation (Fig 2D, E) indicate that a smaller bonded area might function as well against peeling forces and that enlarging the bonded area does not necessarily create a better resistance against tensile stress, which is in accordance with the findings of Bhakta et al.[25] They varied the size of the bonding area from 10 up to 50 mm^2 and concluded that the amount of bonded area meant to resist the peeling forces is irrelevant to the peeling process.

Stress concentrations of CAN (Fig 2C, F) and SFF (Fig 3B, C) are similar at an applied load of 224 and 185 N, respectively. In both cases, cohesive failure of the cement layer is expected. Figure 3A, as explained above, represents a simulated three-unit fixed-fixed RBFPD without a retentive preparation. When loaded from an occlusal direction (Fig 3A, arrow) an average of 185 N is needed for debonding. This is below the estimated maximum of up to 320 N mastication force usually applied in the posterior region, but higher than the recorded average mastication force of 100 N.[31] That two-unit cantilevered and three-unit fixed-fixed RBFPDs nevertheless clinically fulfil their functional requirements is clearly due to the retentive preparations.[4,6,7,9,10,14,16,17,21] It is also clear that our in vitro

Table 3 Mean cement-covered metal surface area% with SD in parentheses

	% on metal			% on enamel		
Luting cement	CAN	SFF	BFF	CAN	SFF	BFF
RelyX ARC	6 (9)^{c}	56 (24)^{bc}	23 (17)^{bc}	100 (0.0)^{A}	100 (0.0)^{A}	100 (0.0)^{A}
Panavia 2.0	47 (18)^{bc}	73 (14)^{b}	46 (12)^{bc}	100 (0.0)^{A}	98 (7)^{A}	100 (0.0)^{A}
UniFix	87 (8)^{a}	100 (0.0)^{a}	100 (0.0)^{a}	100 (0.0)^{A}	99 (4)^{A}	100 (0.0)^{A}

Identical lowercase letters indicate no significant difference per test type for the remaining cement% on the metal.
Identical uppercase letters indicate no significant difference per test type for the remaining cement% on the enamel.

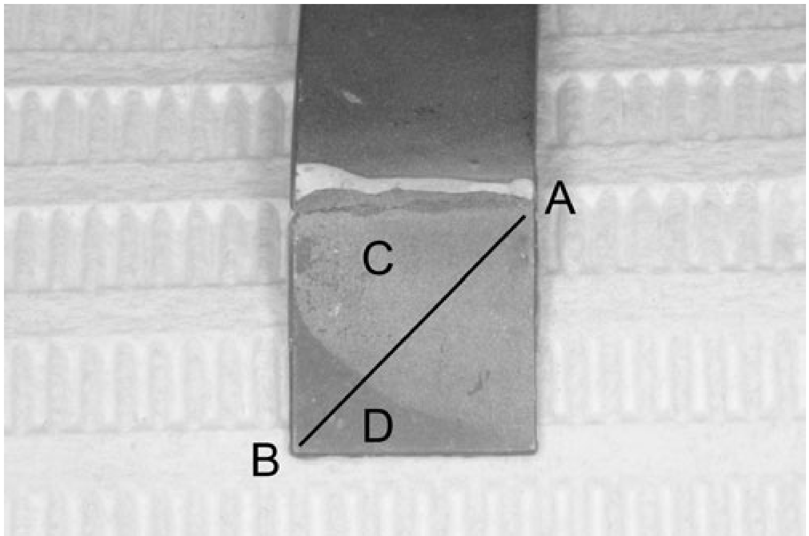

Figure 5 Typical failure pattern of a BFF (bent straight cantilevers) Panavia specimen. Debonding originates from the upper right corner (A) of the luted surface and propagates to the lower left corner (B) as indicated by the diagonal line. The light gray quarter circle section (C) has gradually debonded under the influence of the applied load, while the dark gray section (D) debonded entirely at catastrophic failure.

two-unit cantilevered RBFPDs performed even better than the simulated three-unit fixed-fixed RBFPD, with failure loads of 224 and 185 N, respectively.

In contrast to the relative high failure loads within the CAN and SFF groups, the BFF specimens failed at only 27 N, and the cause of failure is mainly adhesive (Fig 3E, F). The typical failure pattern of all BFF Panavia and UniFix specimens in the laboratory tests (Fig 5) clearly coincides with the stress concentrations in Figure 3F, the stress being at peak values at the point of crack initiation. A complete fractographic analysis of the failure is beyond the scope of this study.

The BFF group (Fig 3D) simulates an anterior three-unit fixed-fixed RBFPD with the incisor and the canine as abutments. Loading the incisor or canine with a load between 27 and 73 N (Table 2), with an accompanying movement of only 17 μm, can lead to failure. These loading forces and tooth movements are well within physiological ranges. Again, retentive preparations will increase the load to failure, but these low forces (between 27 and 73 N) might be a plausible explanation for why three-unit fixed-fixed RBFPDs have in general a lower survival rate than the two-unit cantilevered RBFPDs in similar situations. Clinical evidence for the fact that two-unit cantilevered RBFPDs or straight three-unit fixed-fixed RBFPDs perform better than a curved three-unit fixed-fixed RBFPD is to our knowledge not available, but would be valuable for further design improvements of RBFPDs. Furthermore, in the present study, only load to failure has been studied. One should realize that clinically, debonding occurs as a result of fatigue, where fatigue is defined as repeated loading cycles generating lower stresses than the ultimate strength of the material itself.[32]

While the laboratory tests were carried out with three resin cements, for the FEA only one cement (Panavia F2.0) was chosen. Of the three cements used, Panavia has the highest E-modulus[23,33] (12.8 GPa), while those of RelyX ARC (5.6 GPa)[34] and UniFix (1.8 GPa, manufacturer's data) are much lower. Choosing Panavia, a stiffer cement with its high E-modulus, was a choice for the worst-case scenario. It is reasonable to assume that the stresses within the cement layers of the lower E-moduli cements are more evenly distributed in the cement layer, subsequently leading to lower peak stresses.[11]

Table 4 The different maximum stresses (MPa) observed in the cement layer of the FEA models, with the specific loading situation as depicted in Figures 2 and 3 in parentheses

Stress	CAN (2AD)	CAN (2BE)	CAN (2CF)	SFF (3ABC)	BFF (3DEF)
Solid major principal stress	88	77	122	125	102
Solid S_z	55	63	13	23	74

Neither the patient nor the dentist wants to be confronted with partially debonded RBFPDs for reasons of tooth preservation. Decay underneath a partially debonded RBFPD usually goes undetected for some time until a certain extent has been reached. If crack initiation and propagation within the cement layer could be avoided, it is reasonable to expect an extended longevity. Debonding limits durability, therefore, a well-defined design may prolong longevity. Evidence-based design principles regarding two-unit cantilevered RBFPDs do not exist.[14-16,35] To decrease stress concentrations in the cement layer Bhakta et al[25] have suggested a design alteration with the attachment point of the cantilevered pontic located centrally on the bonded area of the beam. Adding retentive proximal grooves, guide planes, a 180° wraparound, and a chamfer have proven clinically effective on three-unit fixed-fixed RBFPDs.[4,6,7,9,10] A number of studies[17,20,35] indicate that the same provisions offer enhanced retention for the two-unit cantilevered alternative.

Conclusion

Within the limitations of the methodology of this in vitro study, the failure mechanisms of two-unit cantilevered and three-unit fixed-fixed RBFPDs have been revealed. The results of both the laboratory tests and the FEA are complementary. The FEA results make clear which part of the interface is prone to the highest stress levels. The abutment preparations need a design that avoids high interfacial stresses to help prevent debonding. The low failure loads for the BFF group, representing three-unit bent fixed-fixed RBFPDs, when compared to their straight counterparts, indicate that clinically, a reserved attitude needs to be maintained with regard to three-unit fixed-fixed RBFPDs spanning a clearly curved part of the dental arch.

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