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Fracture Strength and Fracture Patterns of Root-filled Teeth Restored With Direct Resin Composite Restorations Under Static and Fatigue Loading

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Clinical Relevance

Root-filled teeth suffer substantial loss of tooth structure from restorative and endodontic procedures. A direct adhesive restoration will help preserve the remaining tooth structure as long as it provides enough strength and marginal integrity.

SUMMARY

Aim: To assess fracture strength and fracture patterns of root-filled teeth with direct resin composite restorations under static and fatigue loading.

Methodology: MOD cavities plus endodontic access were prepared in 48 premolars. Teeth were root filled and divided into three restorative groups, as follows 1) resin composite; 2) glass ionomer cement (GIC) core and resin composite; and 3) open laminate technique with GIC and resin composite. Teeth were loaded in a servohydraulic material test system. Eight samples in each group were subjected to stepped fatigue loading: a preconditioning load of 100 N (5000 cycles) followed by 30,000 cycles each at 200 N and higher loads in 50-N increments until fracture. Noncycled teeth were subjected to a ramped load. Fracture load, number of cycles, and fracture patterns were recorded. Data were analyzed using two-way analysis of variance and Bonferroni tests.

Results: Fatigue cycling reduced fracture strength significantly ($p<0.001$). Teeth restored with a GIC core and a laminate technique were significantly weaker than the composite group (379±56 N, 352±67 N vs 490±78 N, $p=0.001$). Initial debonding occurred before the tooth underwent fracture. All failures were predominantly adhesive, with subcrestal fracture of the buccal cusp.

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Conclusions: Resin composite restorations had significantly higher fracture strength than did other restorations. Fatigue cycled teeth failed at lower load than did noncycled teeth.

INTRODUCTION

Root-filled teeth suffer substantial loss of tooth structure as a result of caries and subsequent restorative procedures, making them vulnerable to fracture if they are not adequately restored.[1] Given their low cost, resin composites are becoming increasingly common in the restoration of root-filled teeth, to an extent replacing coronal coverage restorations. Concerns thus arise with regard to the strength of such restorations, and the problem of marginal leakage and its sequelae must also be considered. The use of low shrinkage composites and new generations of dentin bonding agents has been investigated,[2-4] and in terms of fracture resistance, favorable results have been reported in both experimental and clinical studies.[5-7] However, the problem of marginal leakage continues to be a concern. Hence, different liners, including flowable composites, resin-modified, and conventional glass ionomer cements (GIC), have been investigated both as a core and in a laminate ("sandwich") technique and have been found to be beneficial in reducing marginal leakage.[3,8-11]

Cusp fracture of restored teeth with or without root canal therapy is a common finding clinically. The most common cause has been reported to be a high impact force as a result of biting on a hard object, with tooth anatomy and type and size of restoration being contributing factors.[12] Fatigue-related failure is also a major concern,[13] with cuspal fracture occurring after prolonged function. Experimentally, cyclic fatigue might have more drastic effects on fracture strength than a static load as a result of the initiation and propagation of cracks within tooth structure and restorations.[14,15] Fatigue fracture can occur at the point at which maximum stress occurs, which in the case of adhesive restorations is the tooth-restoration interface.[16]

Fracture resistance of teeth has been used as a measure of the effect of cavity preparation and restoration on tooth strength. Both destructive and nondestructive techniques and the creation of mathematical models for analyzing stress distributions have been used.[17-19] The clinical relevance of the static load to failure approach is questionable, as the load usually applied in these studies is well above the natural biting force. Variable numbers of load cycles at physiological loads preceding ramped load to fracture are commonly included to simulate normal oral function. Teeth are then subjected to static loading to fracture. Typically, however, the number of cycles represents only weeks or months of normal chewing cycles. Nevertheless, for comparison between restorative techniques and materials, static loading with or without cyclic loading can still be considered a valid approach.

The alternative to static load is fatigue testing, in an attempt to represent physiological mastication and fatigue failure of teeth or restorations. The number of cycles to failure at physiological loads (up to 100 N) is extremely high and makes fatigue testing of restored teeth impractical in many instances.[20] As an alternative, stepped fatigue loading, with a progressively increasing load for a specified number of cycles, is being used for fatigue testing of teeth.[21,22] A stepped load protocol was applied in this study; this protocol could be considered as an adequate compromise between the classic ramped load and the time-consuming conventional fatigue test (high number of cycles at low load).

The aim of the study was to assess the fracture resistance and fracture patterns of root-filled maxillary premolars with similar cavity design and three different direct restoration techniques using resin composite under static and fatigue loading.

MATERIALS AND METHODS

Tooth Selection and Mounting

Forty-eight extracted intact noncarious maxillary premolars of similar size (as measured from both bucco-lingual and mesio-distal directions of the occlusal surface of the crown using a digital caliper) were used. The selected teeth were mounted vertically in epoxy resin in polyvinyl chloride plastic rings without a simulated periodontal ligament, since in a previous study,[23] a simulated periodontal ligament (PDL) did not influence fracture strength under these conditions of testing. The epoxy resin mounting extended to 2 mm below the cemento-enamel junction (CEJ) to simulate the alveolar bone level. The project was approved by the Ethics in Human Research Committee of the University of Melbourne. Teeth were stored in 1% chloramine T solution in distilled water (pH=7.8) (Sigma-Aldrich Co, St Louis, MO, USA) for two weeks.

Cavity Preparations

Extensive MOD cavities, plus endodontic access with the proximal axial walls removed, were prepared as previously described,[23] using a tungsten carbide round-ended fissure bur (Komet H21R, Brasseler, Lemgo, Germany) in a high-speed handpiece with water coolant. The bucco-lingual width of the occlusal isthmus was one-third of the width between buccal and lingual cusp tips, and the bucco-lingual width of the proximal box was one-third of the bucco-lingual width of the crown. The gingival floor of the box was 1 mm coronal to the CEJ; total depth of the proximal box occluso-gingivally was 6 mm. The cavosurface margins were prepared at 90°, and all internal angles were rounded. Endodontic access included the removal of all dentin between the proximal box and the pulp chamber.

Root canals were prepared using the ProTaper rotary nickel-titanium system (Dentsply, Maillefer, Ballaigues, Switzerland) with 1% NaOCl irrigation between instruments and a final flush with 17% ethylene diamine tetraacetic acid solution and root filled using gutta percha and AH Plus root canal sealer (Dentsply, Maillefer Detrey, Konstanz, Germany). Gutta percha was removed to 2 mm below the CEJ. Excess sealer was removed with a cotton pellet moistened with alcohol.

Restoration

The teeth were divided randomly into three groups of 16 teeth each using a random numbers table and were restored as follows (Figure 1).

Group 1 (Resin Composite)—The entire cavity preparation was etched with 37% phosphoric acid (Super Etch, SDI Limited, Bayswater, Australia; batch No. 030648) for 20 seconds, rinsed with air-water spray for 10 seconds, and blot dried (wet bonding in accordance with the manufacturer's instructions). A bonding agent (Adper™ Single Bond, 3M ESPE, St Paul, MN, USA; lot No. 184141) was applied and light-cured for 20 seconds, and the cavity was incrementally restored with OD3 shade resin composite with a matrix band in place (Glacier, SDI Limited;batch No. 071089). Three increments were placed and cured using a LED light-curing source (Bluephase C8, CE Ivoclar, Vivadent AG, F1-9494 Schaan, Liechtenstein) at an intensity of 800 mW/cm^2 for 40 seconds. The first increment was packed into canal orifices and both proximal boxes to a depth of approximately 1 mm. The last two increments covered the entire mesio-distal and bucco-lingual width of the cavity. Restorations were finished and polished using a flame-shaped diamond bur (Komet Dental, Brassler, Germany) and Sof-Lex finishing discs (3M ESPE).

Group 2 (GIC Core and Resin Composite Restoration)—Prior to restoration with composite, a 10% polyacrylic acid dentin conditioner was applied for 10 seconds and rinsed for five seconds, and then a conventional GIC base (Fuji VII, lot No. 0811111; GC Corporation, Tokyo, Japan) was placed above the gutta percha to reproduce the floor of a MOD cavity. Acid etching and the bonding agent were then applied to the cavity wall and over the GIC, and the teeth were then restored with resin composite, as in Group 1.

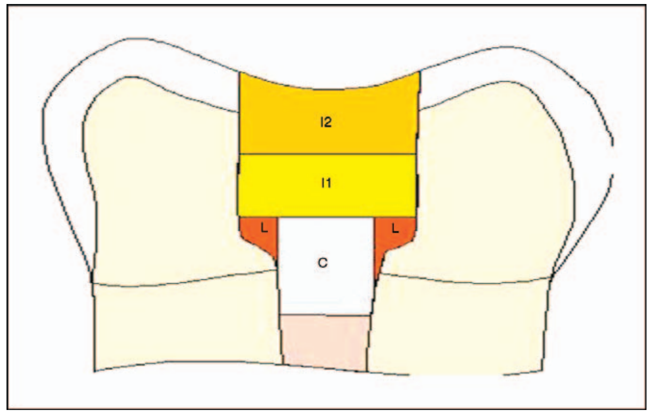

Figure 1. *A diagram representing the three restoration techniques. C (shown in gray) represents the GIC core, inserted into the coronal part of the canal space. The restoration shown in the orange area (L) plus the gray area shows the area filled when a laminate restoration was used, while the coronal resin composite placed in two increments (I1 and I2) is shown by the coronal part of the cavity.*

Group 3 (Open Laminate Technique and Resin Composite Restoration)—Prior to restoration, a 10% polyacrylic acid dentin conditioner was applied for 10 seconds and rinsed for five seconds and then a 1-2 mm glass ionomer base (Fuji IX, lot No. 0902245; GC Corporation) was placed above the gutta percha and into the proximal boxes to a thickness of 1.5-2 mm at the proximal surfaces. The teeth were then restored with two increments of resin composite, as described above.

After restoration, teeth were stored in an incubator at 37°C in 100% humidity for 24 hours before testing. Teeth in each restorative group were then randomly allocated to either static or fatigue loading subgroups (eight teeth each).

Static and Fatigue Loading

All teeth were subjected to fracture testing using either a static load or a stepped cyclic loading sequence.[22] Loading was at 45° to the long axis of the tooth, on the palatal incline of the buccal cusp, using a rounded steel loading tip measuring 1.3 mm in diameter in a servohydraulic material test system (MTS model 801, MTS Corporation, Eden Prairie, MN, USA). Noncycled teeth were subjected to a

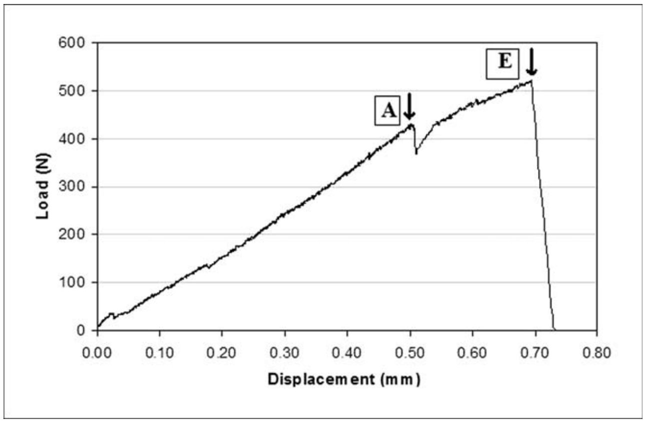

Figure 2. *Typical load displacement curve showing the initial failure (A) and the final fracture (E) loads.*

ramped load at a rate of 0.5 mm/min until fracture. Fatigue-tested subgroups were subjected to cyclic loading, with a preconditioning load of 100 N (5000 cycles, 5 Hz), followed by stepped loads of 200 N and 250 N and higher loads in 50-N increments, as needed, for 30,000 cycles each (3-5 Hz) until fracture. Fracture load (N), number of cycles, and fracture patterns were recorded. Fracture strengths were compared statistically using two-way analysis of variance with Bonferroni test for multiple comparisons.

Mode of failure (adhesive, cohesive) was investigated by light microscopy at 20× magnification. For purposes of data analysis, the failure load and fracture load were analyzed separately. Failure load was defined as the load at which debonding occurred; if a separate debonding event did not occur, then the load at fracture was considered to be the same as the failure load. Fracture load was defined as the load at which complete cusp fracture occurred. For teeth subjected to cyclic loading, the number of cycles to failure and fracture were also recorded separately.

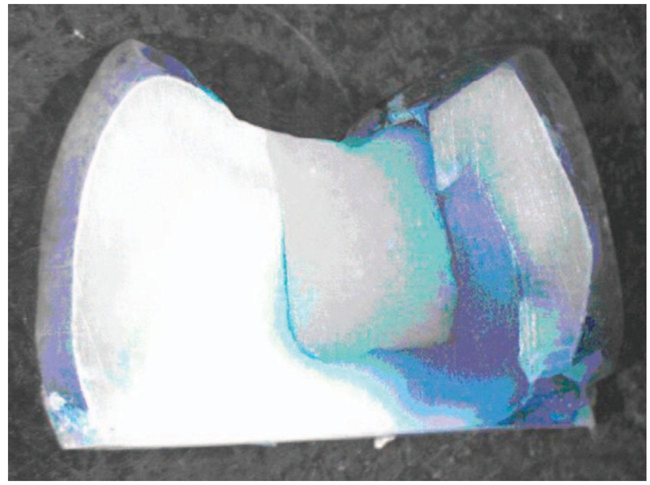

Figure 3. *Light micrograph (20× magnification) of a section of a tooth restored with resin composite and showing debonding without fracture. The tooth was immersed in methylene blue stain before sectioning and shows dye penetration along the interface between the buccal cusp and restoration, extending from the buccal occlusal surface across the base of the cavity to the palatal interface. No evidence of a fracture of the buccal cusp is present.*

RESULTS

Debonding Failure vs Fracture

A common finding in the study was the occurrence of an initial sudden debonding at the tooth-restoration interface, accompanied by an audible, sharp cracking sound that could also be detected in the load-displacement curve by a sudden drop in load (Figure 2), before the tooth underwent actual fracture. This phenomenon was observed in most teeth (31/48) undergoing both static and cyclic loading (Table 1). Debonding at either the buccal or palatal interface of the restoration was confirmed in additional teeth by stopping the load immediately after the sound was heard; staining the tooth with methylene blue and examining both the restoration margins and cross sections of the tooth demonstrated that marginal failure had occurred without cuspal fracture (Figure 3). A similar result was observed with silver staining

Table 1: *Pattern of Failure in the Three Restoration Groups in Response to Static and Fatigue Loading*

		Separate Debonding Event?		Fracture Site[a]		
Restoration Type	Load Pattern	Yes	No	Buccal	Palatal	Other
Composite	Static	5	3	6	1	1
	Fatigue	5	3	6	0	2
GIC liner	Static	6	2	7	1	0
	Fatigue	6	2	2	5	1
Open laminate	Static	3	5	4	4	0
	Fatigue	6	2	3	4	1

[a] *Fracture site refers to the tooth-restoration interface at which debonding occurred, accompanied by buccal cusp fracture. "Other" refers to fracture within the buccal cusp (two teeth), root fracture (two teeth), or debonding at both buccal and palatal interfaces (one tooth).*

Table 2: *Mean Failure and Fracture Loads in Newtons (N) for the Test Groups With and Without Cyclic Fatigue*

	Ramped Loading		Cyclic Fatigue	
Group	**Failure Load ± SD**	**Fracture Load ± SD**	**Failure Load ± SD**	**Fracture Load ± SD**
Composite	390 ± 126	490 ± 78	310 ± 68	310 ± 68
GIC liner	326 ± 58	379 ± 56	260 ± 69	265 ± 65
Open laminate	330 ± 57	352 ± 53	261 ± 69	264 ± 67

Abbreviation: SD, standard deviation.

(not shown). The load at which this debonding occurred was recorded and is referred to as failure load; the frequency of its occurrence in the different groups is presented in Table 1. Most such teeth fractured soon after debonding, but some teeth survived a considerably higher load or many additional load cycles before complete cuspal fracture occurred.

Failure Load

Load at failure was significantly lower in the groups subjected to fatigue cycling than in the static loading groups ($p<0.001$; Table 2). No differences were found among the different types of restorations ($p=0.098$). The number of cycles to failure in the fatigue testing groups varied over a wide range (5800-128,012 cycles; Table 3), with no significant differences among restoration types.

Fracture Load

Fatigue cycling had a highly significant effect in reducing fracture strength compared with static loading ($p<0.001$; Table 2). The type of restoration also had a significant impact on the fracture load ($p<0.001$). Teeth restored with resin composite alone were significantly stronger ($p=0.001$) than the liner and laminate groups (fracture 490±78 N vs 379±56 N and 352±53 N, respectively, in the static loading groups, and 310±68 N vs 265±65 N and 264±67 N in the fatigue cycling groups). The number of cycles to fracture varied from 9000 to 128,012 cycles, with no significant differences among groups ($p=0.36$; Table 3).

Failure and Fracture Modes

All failures occurred by debonding at the buccal or palatal interface between the restoration and the cavity wall, except for two cases of fracture within the buccal cusp and two cases of root fractures (Table 1). In the open laminate group, debonding was evenly distributed between the buccal and palatal interfaces, while other restorations failed predominantly at the buccal interface. Fracture almost always (45/48) involved the buccal cusp, with the crack initiating at the buccal line angle of the proximal box and extending obliquely to a subcrestal fracture on the buccal root surface (Table 1).

DISCUSSION

Teeth are subjected to repetitive occlusal loading during normal function, estimated to reach loads of up to 300 N (but more typically loads of 50-60 N) and approximately 1,200,000 cycles per five years.[24-29] Thus, it is more likely that clinical restorative failures many years after restoration may be a function of fatigue rather than a single episode of high occlusal stress.[13,29] This repetitive stress is not easy to replicate in experimental studies. Fatigue testing is a lengthy procedure and is widely considered to be impractical for testing teeth and restorative materials, especially if physiological loads are used during testing.[30,31] The use of stepped loading in this study was based on established experimental protocols by previous studies of indirect and direct coronal coverage restorations.[16,21,22] Testing begins with a low preconditioning load for 5000-10,000 cycles and then proceeds with 200-N increments at a maximum of 30,000 cycles at each

Table 3: *Number of Cycles to Failure (Debonding) and Fracture in the Three Restoration Groups Subjected to Fatigue Testing*

Restoration Type	Cycles to Failure,[a] Mean (Range)	Cycles to Fracture,[b] Mean (Range)
Composite	72,898 (9000-127,085)	75,208 (18,095-127,085)
GIC liner	48,447 (6502-128,012)	48,499 (6583-128,012)
Open laminate	47,297 (5800-126,463)	52,539 (5800-127,805)

[a] *Failure was defined as debonding of the restoration (see text for greater detail).*
[b] *Fracture was defined as the actual cusp or tooth fracture.*

load until fracture occurs. The only modification in our protocol was reducing the preconditioning load to 100 N and then increasing it in 50-N increments, based on the mean fracture loads of comparable groups in a previous experiment with ramped loading.[23] The earlier studies mentioned above used stepped fatigue testing as the standard protocol for testing and did not compare the effect of fatigue on fracture strength compared to static loading.

The number of cycles varied widely among teeth within groups, and significant differences between groups could not be demonstrated. Overall, cyclic loading negatively affected the fracture strength of teeth and may be considered an essential step in evaluation of restorative materials; however, for the sake of comparison between different techniques, the ramped load approach can still be an acceptable approach. Bolhuis and others[32] looked at the effect of fatigue loading (1 million cycles vs control) on the retention of carbon fiber post–resin composite core of maxillary premolars and found it an insignificant variable compared to the effect of cement type. Jantarat and others[29] found cyclic fatigue to cause minimal cumulative cusp displacement and concluded that it may not contribute directly to cuspal damage but rather to bond failure between the restoration and the tooth. However, our results showed almost comparable results of frequency of bond failure between ramped and fatigue-tested groups, which implies that the bond yields first regardless of the type of loading.

Of interest is the fact that failure patterns were consistent in the three restoration groups regardless of the type of loading. Almost all teeth showed debonding at the tooth-restoration interface (predominantly at the buccal margin), with fracture initiating at the buccal line angle of the proximal box and extending obliquely to subcrestal fracture of the buccal cusp. The pattern of failure was identical to that reported previously,[23,33,34] although fracture patterns vary among studies depending on tooth mounting and the direction and location of occlusal loading.[7,35]

Separate debonding was a common event before fracture in the three groups with both types of loading, similar to the findings of Hatta and others[36]; its occurrence ranged from 37% in the open laminate static load group to 62% in the composite groups and up to 75% in the fatigue-cycled open laminate group and the liner groups. The fact that most teeth survived additional cycles or higher loads before actual cusp fracture implies that the restoration did not strengthen these teeth. Otherwise cuspal fracture would occur immediately after debonding at the tooth-restoration interface. This observation also raises a concern if debonding without fracture happens clinically. If the restoration fails and a gap is open (mostly unseen) well before the cusp fractures and symptoms appear, this will invite secondary caries and may negatively affect the future restorability of the tooth. Further investigations are needed to demonstrate where failure initiates and the pattern of crack propagation.

Resin composite restoration was significantly stronger than the liner and laminate groups in terms of fracture but not in terms of failure. This could be explained by the higher mechanical properties of resin composite compared to GIC[10]; however, it is worth mentioning that, in some countries, Fuji VII has been superseded by the light-cured Fuji Triage, which may have better mechanical properties. This result is in agreement with some previous findings[2,8,37] but contrary to other studies.[34,38] Differences could be related to variation in the method and point of loading, type of GIC used (conventional vs resin modified), thickness of the base, type and size of cavity preparation, and anatomical variation of teeth. Despite the ability of GIC to bond to dentin, it was not able to shift the fulcrum point for cuspal fracture to a higher level than that proposed by Hood[39]—the buccal line angle of the proximal box, and therefore did not change the fracture pattern to a more favorable one (supracrestal).

Although the use of a GIC base has been shown to be beneficial in terms of improving the proximal marginal seal of resin composite restorations, particularly the resin-modified types,[9,11,40] attention should be paid to the fact that GIC has lower mechanical strength than does resin composite, and, therefore, it should be used in minimum thickness to achieve this goal without compromising the strength.

CONCLUSION

- Resin composite restoration was significantly stronger than both the glass ionomer core and laminate techniques.
- Bond failure remains a major concern with resin composite restorations.
- Fatigue cycling had a negative effect on the fracture strength of restored teeth.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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