Co-Influence of Restoration Bonding and Inlay Cavity Design on Fracture Load of Restored Tooth

Keywords

Bonding
Stress Distribution
Inlay
Cavity Design
Ultimate Fracture Load

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Received: 12.01.2023
Accepted: 10.06.2023

doi: 10.1922/EJPRD_2510Yli-Urpo08

ABSTRACT

Introduction: The aim of this study was to investigate the co-influence of indirect mesio-occlusal-distal (MOD) cavity geometry and inlay restoration bonding on quasi-static fracture load of the restored tooth. Methods: Forty-eight intact human molar teeth were selected and prepared for standardized edge-shaped or round-shaped MOD cavities. The resin composite (Cerasmart, GC) inlays were bonded with the state-of-the-art inlay bonding protocol or with intentionally deteriorated bonding using n-hexane-wax solution for preconditioning. Restored teeth were loaded along the long axis of the tooth. Ultimate fracture load was recorded, and the type of fracture was visually determined and classified. Statistical analysis of load values was performed by Kruskal-Wallis test. Results: Round-shaped cavity design with bonded restoration presented the highest fracture load (1658N). Bonding had significant influence on the fracture load of round-shaped cavity design (p=0.0003), whereas cavity design had no influence when the bonding was deteriorated (p=0.8075). In the case of deteriorated bonding, either the inlay or tooth fractured separately whereas in the bonded inlays fractures were commonly found both in the tooth and inlay. Conclusions: According to this study, bonded inlay restoration increased fracture resistance, while cavity design had no statistical difference on fracture resistance of the restored tooth.

INTRODUCTION

Thousands of tooth restorations are placed every day during dental treatments in dental healthcare services. When a tooth is prepared for a filling, it is intended to last for a long time. The objective is to restore tooth for adequate strength and function, even though loss of dental tissue during the preparation of cavities may make a tooth weaker. According to earlier studies, cavity geometry has a significant effect on a tooth's fracture resistance, and in that sense, on the survival of a restored tooth.[1-4] In order to resist fractures and increase a tooth's lifespan, cavities for indirect restorations are recommended to be prepared rounded in all intracoronal angles.[5,6] There are multiple reports evidencing the importance of favorable cavity designs for optimal stress distribution. Finite-element-analysis (FEA) by Hubsch *et al*. (2002), suggested that stress fields might be singular at the margins of restorations with rectangular margins, and thus reduce fracture strength, whereas beveled margins were found to reduce tensile stress.[7] Rounded cavity shape significantly reduced stress between the tooth and restoration.[7] They also suggested that adhering restorations will perform better from a mechanical point of view if an appropriate cavity shape is selected.[7]

According to Shi *et al*. (2008), FEA revealed that most vulnerable areas in terms of debonding are within the enamel-composite junctions.[8] The optimized cavity shapes can potentially prolong the life of restorations and reduce the incidence of fracture in restored teeth.[8]

However, there are no data on how much round internal preparation angle and deteriorated bonding effect a restored tooth's fracture resistance and load-bearing capacity. Recommendations assume that rounded intracoronal angles of tooth cavities allow stress caused by the load to distribute over a large area.[5,7,9] In addition, rounded angles give more strength and higher fracture resistance to restored tooth, even though restorations may not return strength to the level of an intact tooth.[10]

In the case of indirect restorations, cavity design and consequently optimal stress distribution, are not always restricted to minimal removal of caries. Li *et al*. (2010) studied strengthening of a model composite restoration using shape-optimization.[11] They concluded that a T-shaped cavity reduced interfacial stress between the restoration and artificial premolar teeth and increased fracture resistance compared to the MOD parallel wall design and undercut design although it required a higher amount of dental tissue preparation.[11] The T-shaped cavity reduced tensile stress but increased shear stress in tooth.[11]

Not only inadequate geometry of the cavity, but also careless restoration bonding are typical reasons for tooth fractures and failed restorations and treatment outcome. Liberman *et al*. (1990) studied the resistance of cavity walls to vertically applied occlusal forces using unbonded restorations and teeth restored with amalgam and composite resin materials.[12] They concluded that bonded composite restorations significantly increased the fracture resistance of a 2mm wide cavity wall compared to unbonded amalgam restorations and unrestored teeth.[12] The level of dentists' cautiousness and awareness of used materials conclusively affects the success of restorations to successful restorations. For successful bonding, it is important to know the properties of restoration materials, adhesion systems and their weaknesses and advantages in different situations. The purpose of this study was to investigate the influence of cavity design and restoration bonding to the quasi-static fracture load of restored tooth using extracted human molars with two different cavity designs.

METHODS

MATERIALS

To study the effect of the geometry of cavities' internal angle and bonding of restoration on fracture strength of restored tooth, 48 closely similar sized intact human molar teeth were selected. The teeth were randomly divided into four groups. Standardized edge-shaped MOD-cavity bottom geometry was prepared for two groups (groups 1 and 2) and standardized rounded MOD-cavity bottom geometry was prepared for the remaining two groups (groups 3 and 4). Description of the groups (deteriorated bonding = non-bonded):

1. Edge-shaped cavity bottom, bonded restoration
2. Edge-shaped cavity bottom, non-bonded restoration
3. Round-shaped cavity bottom, bonded restoration
4. Round-shaped cavity bottom, non-bonded restoration

FABRICATION AND BONDING OF RESTORATION

Materials used in the study are listed in Table 1. Standardized preparations were 4 mm wide and deep. Preparations were standardized by sketching 4 mm dimensions carefully on tooth. During the preparation, one model restoration of both designs was used to fit in cavity preparations as precisely as possible. MOD inlay cavities were prepared with a 5-degree divergence to prevent undercuts. Two different cavity bottom geometries were used: edge-shaped and rounded preparations. Cavity wall – bottom angulation was 95° degrees and radius of the round-shaped cavity was 1.2 mm. Prepared cavities were scanned, and restorations were milled from hybrid ceramic Cerasmart blocks (CERASMART270 14 A2 HT) using CAD/CAM technology (Omnicam, CEREC AC SW5.1.3 and CEREC MC XL). To mill anatomically as similar occlusal surfaces as possible, each tooth was scanned using the Biogeneric Copy program with one model restoration. In restorations, anatomical shape was retained but central fossa was set slightly deeper to direct the load to cusps instead of the central fossa of restoration. The metal ball was in contact with the restoration without touching the enamel surface. All used materials for bonding are listed in Table 1.

Bonding of the restoration was implemented using 2 etchants, 2 primers and self-adhesive resin cement. Cerasmart inlay restoration was etched using 4.5% hydrofluoric acid (IPS Ceramic Etching Gel) for 60 s, rinsed with distilled ultrapure type 1 water and air-dried. In tooth cavity, enamel was etched selectively with 37% phosphoric acid (Scotchbond Universal Etchant) for 15 s, rinsed with distilled type 1 water and air-dried.

G-Multi Primer (GC) was applied onto restoration surface and air-dried. Adhesive Enhancing Primer (GC) was applied to tooth cavity, brushed 10 s according to manufacturer's instructions and air-dried for 5 s.

Primer air drying helps to spread the primer on the surface to accomplish even surface of primer to cavity and restoration surfaces, and evaporate primer solvent, ethanol, in both used primers.

Self-adhesive resin cement (G-CEM ONE Twin Refill A2) was applied onto the cavity before fitting the restoration. Excessive cement was removed, and bonding cement was light-cured for 10s with LED light (D-Light Pro, high power 1400 mW/cm^2). A light-curing tip was held in contact with to the occlusal surface of the tooth during light-curing.

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Table 1. Materials used in this study. MDP= 10-Methacryloyloxydecyl dihydrogen phosphate; MDTP = 10-methacryloyloxydecyl dihydrogen thiophosphate; 4-MET = 4-[2-(methacryloyloxy)ethoxycarbonyl]phthalic acid; Bis-MEPP = bisphenole A ethoxylate dimethacrylate UDMA= urethane dimethacrylate; DMA= dimethacrylate.

Material	Composition	LOT	Manufacturer
IPS Ceramic Etching Gel	4.5% Hydrofluoric acid	Y03912	Ivoclar Vivadent, Schaan, Liechtenstein
Scotchbond Universal Etchant	37% Phosphoric acid	6115193	3M ESPE, Neuss, Germany
G-Multi Primer	Ethyl alcohol (90-100%), MDP, MDTP, silane	2102051	GC Europe, Leuven, Belgium
Adhesive Enhancing Primer	Ethyl alcohol (25-50%), MDP, 4-MET, MDTP	2012011	GC Corporation, Aichi, Japan
Self-Adhesive Resin Cement	UDMA, DMA, MDP, inhibitor, initiator	2010281, 2010291	GC Europe, Leuven, Belgium
Cerasmart270	71wt% silica (20nm) and barium glass (300nm) nanoparticles, Bis-MEPP, UDMA, DMA	2102101, 2102021, 2103011	GC Corporation, Aichi, Japan

In groups 2 and 4, restoration surfaces were not etched, and primer was not applied. Instead, restorations were preconditioned using n-hexane wax solution onto restorations, which disturbed the bonding between cement and restoration, imitating poor quality and careless bonding.

QUASI-STATIC LOADING TEST

Circular cylinder shaped autopolymerizing poly(methyl methacrylate) PMMA blocks were made by mixing together polymer powder and monomer liquid (Self Curing, Vertex-Dental B.V.; AV Soesterberg, The Netherlands) at the ratio of 1 ml monomer liquid to 1.7 g polymer powder. Restored teeth were embedded into PMMA blocks for the loading test by drilling a hole into PMMA blocks, customized for each tooth, in which the teeth were fixed with additional PMMA. The loading test was performed in air at room temperature (RTP) using an LR30K Plus with a 2500N loadcell (Lloyd Instruments/Ametek Inc., Fareham, UK) which loaded restored teeth at the cross-head speed of 1 mm/min using a 5.5 mm diameter metal ball along the long axis until fracture. The metal ball was in contact with the restoration as indicated in Figure 1. Ultimate fracture load in Newtons and load-displacement curves were recorded.

STATISTICAL ANALYSIS

Statistical analysis was performed with the JMP® program (Version 16.1 Pro. SAS Institute Inc., Cary, NC, 1989-2019). Kruskal-Wallis test was used to compare ultimate fracture load values among the groups. Multiple comparisons were performed using Steel-Dwass test. For statistical analysis, statistically significant difference limit value in strength was set at p=0.05.

RESULTS

Both cavity geometry and restoration bonding affected the strength of the tooth. Load-displacement curves showed that in the bonded restorations (groups 1 and 3) the load increased steadily, and no clear signs of pre-cracking were observed. In the non-bonded restorations ultimate fracture loads were considerably lower than with the bonded restorations and the curves showed clearly pre-crack formation during the loading event *(Figure 2)*.

Statistically significant difference was noticed among the groups ($p<0.0001$). Multiple comparisons performed using the Steel-Dwass test are shown in Table 3. In multiple comparisons, no statistical differences were found between the bonded groups 3 and 1 ($p=0.1910$) and between the non-bonded groups 4 and 2 ($p=0.8075$) *(Figure 3, Table 2)*.

Fracture type was visually determined and classified into 3 types. The distribution of fracture types is shown in Figure 4. Fractures of two cusps, i.e., the entire buccal or palatal wall of the cavity was found most often in restored teeth with bonded restorations. The strongest teeth were those having a curved cavity with a bonded restoration (group 3, 1658N) and most of the failure types were cusp fractures *(Figure 4)*. In non-bonded restorations (groups 2 and 4) fractures occurred mainly within the restoration without propagating into the tooth structure.

DISCUSSION

This study aimed to investigate the influence of inlay restorations' bonding and cavity bottom geometry on durability of the restored tooth using a quasi-static loading test. In this study setup, both restorations' bonding and cavity design

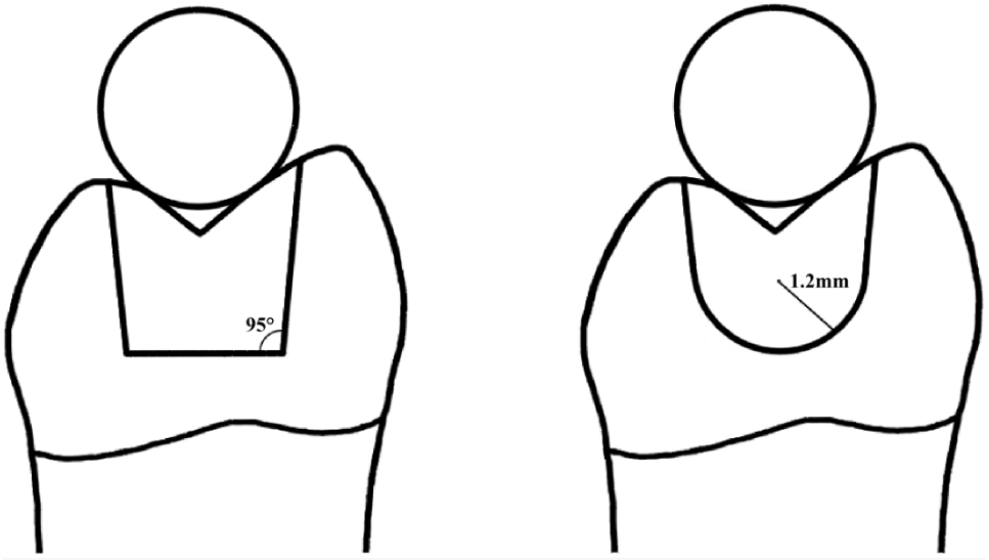

Figure 1: Schematic representation of both edge-shaped and rounded cavity bottom designs, restoration, and metal ball in contact with the inlay restoration in loading test.

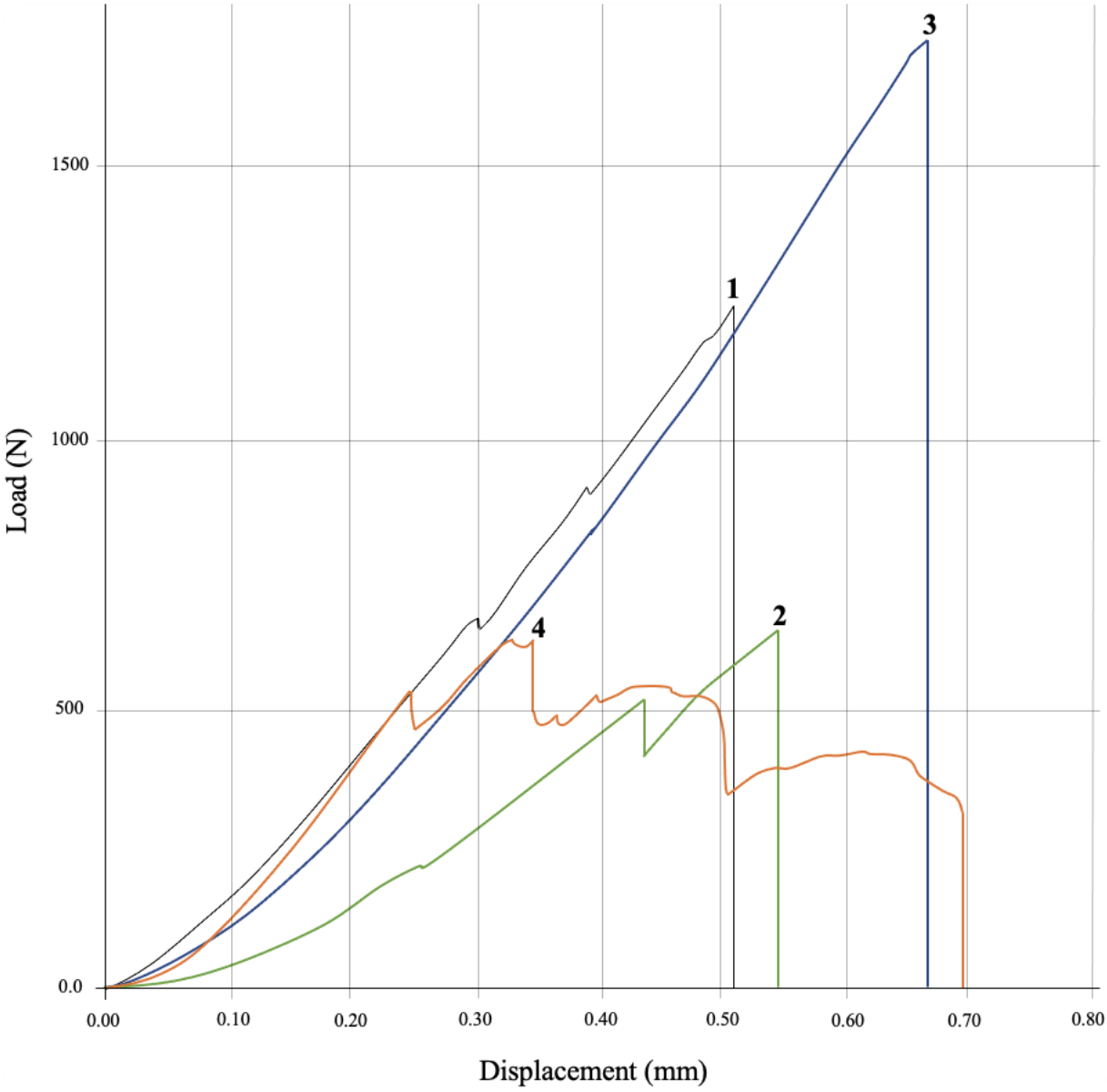

Figure 2: Load-displacement curves according to each group. Groups are described as 1=group 1; 2=group 2; 3=group 3; 4=group 4.

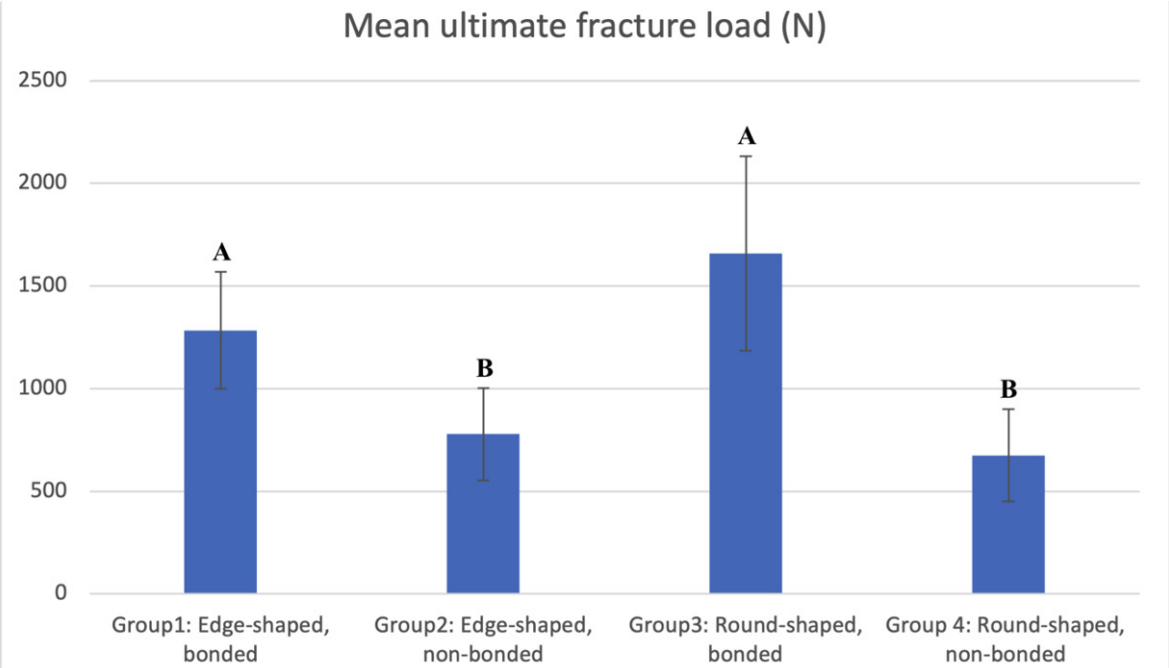

Figure 3: Mean ultimate fracture load and standard deviation (N) for each group. Groups not connected by the same letter on the column are statistically significantly different ($p<0.05$).

Table 2. Compared groups and statistical results from multiple comparisons (Steel-Dwass test).

Compared groups	P-value
Group 3, Group 4	p=0.0003
Group 4, Group 1	p=0.0003
Group 3, Group 2	p=0.0006
Group 1, Group 2	p=0.0022
Group 3, Group 1	p=0.1910
Group 4, Group 2	p=0.8076

influenced the ultimate fracture load and fracture propagation of the restored teeth. In general, bonding had a higher influence on ultimate fracture load than cavity bottom design per se. In case of both rounded and edge-shaped cavity designs, in the bonded restorations the fracture crossed through the restored teeth and majority of the fractures were more destructive for the teeth, whereas in non-bonded teeth failure occurred mostly within the restoration, without propagating into the tooth structure.

The highest ultimate fracture load was found with teeth having a round-shaped cavity design and bonded restoration. Stress was distributed from the restoration via adhesive interface to the entire tooth structure. The tooth with the bonded restorations formed a so-called unibody design where even load transfer from the restoration to tooth eliminates the stress concentrations.[13] In restorations of this kind the cohesive strength of the restoration material obviously has an impact on the fracture initiation and propagation. In this study the restoration material was a well pre-polymerized cross-linked particulate filler resin composite with flexural strength that has shown good mechanical properties which explained the expected good results.[14] For load transfer from the indirect restoration to adjacent dental tissues, the bonding of the luting cement needs to be adequately high both to the restoration and dental tissues. Cerasmart and the similar restorative materials have exposed glass filler particles and cross-linked polymer matrix on the bonding surface.[15] Long term durable bonding is challenging because cross-linked polymer matrix does not allow dissolving of the luting cement monomers to take place and hydrolytic stability of the adhesion of luting cement to the exposed glass fillers cannot be guaranteed.[16] However, the recently introduced ethyl alcohol containing primer (G-Multi Primer) used in this study have shown beneficial bonding effect also to the cross-linked polymer substrates which can in part explain the results of the present study.[17] This effect has been demonstrated with different resin luting cements as well.[18] Bonding of resin cement to the tooth substance was ensured by selective etching of the enamel margins before applying the adhesives.[19]

In this study, edge-shaped cavities fractured mainly at the point of the edge as earlier revealed.[20] This finding can be explained by the differences in stress distribution between the two geometries: in the loading test of round-shaped cavities, loading strains the restorations and causes cuspal deflection, which accumulates stress caused by loading around the rounded structure, whereas in the edge-shaped cavity, stress is concentrated mainly at the point of the sharp edge and therefore increases in the magnitude of stress concentration predisposes the preparation to cuspal fracture as reported

	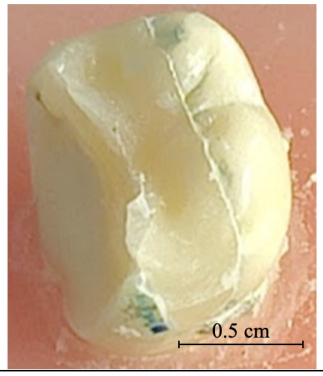	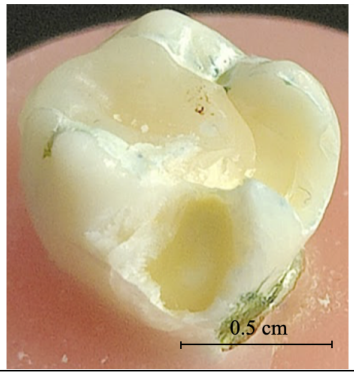	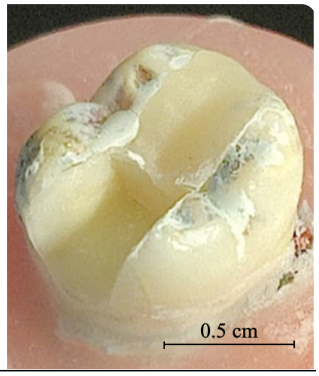
Group1: edge-shaped, bonded	**11**	**1**	
Group2: edge-shaped, non-bonded	**2**	**3**	**7**
Group3: round-shaped, bonded	**8**	**4**	
Group4: round-shaped, non-bonded	**1**		**11**

Figure 4: Distribution of fracture types in each test group. Fractures were classified into 3 types: 1) two cusps fracture (on the left); 2) one cusp fracture (middle); 3) inlay fracture (on the right).

in various FEA analyses.[7,9,12] This accounts the advantageous design of the rounded cavity in tooth cavities also as per this study, and fracture occurs under higher loading forces compared to the edge-shaped cavity in bonded restorations. Earlier Chai *et al.* (2017) concluded that by increasing the cavity wall thickness/depth-ratio, the fracture resistance of a tooth increases regardless of whether it has an edge-shaped or rounded MOD-cavity bottom geometry.[20] Increasing MOD-cavity wall depth and decreasing wall thickness obviously result in a weaker structure, but the cavity design might also reduce stress and increase the strength of restored tooth despite the higher amount of tooth preparation.[11] In this study, a slight variation in cavity wall thickness (SD ±0.28 mm) and depth (SD ±0.46 mm) did not seem to significantly affect the results, neither did the marginally more conventional preparation of a rounded design in intracoronal angles.

Optimized cavity design has also been studied to reduce interfacial stresses between tooth and restoration.[8] However, in this study there were no differences in fracture loads between non-bonded edge-shaped or rounded designs. This might be due to the loading setup: the steel ball was in contact with the restoration without contact to the tooth surface, which causes stress accumulation within the restoration and bonding preventing transmission of stress to adjacent tooth structure. If the steel ball would have been in contact with the tooth surface, loading would have been applied to cusps and the effect of internal line angles of cavities with unbonded restorations perhaps would have been considerable in the non-bonded teeth as in the previous study.8 Some previous studies have shown that stress is typically concentrated on the restoration-tooth interface which enhances the risk of cuspal failures.[8,9,20] According to FEA by Couegnat *et al.* (2006) high-stress areas especially in composite restorations occur along the interface when the restoration bonding is weak or non-bonded when static loading is directed to the restoration.[9] This explains the finding of non-bonded restorations in this study that the stress did not transmit to the tooth structure, which remained intact in most samples and fracture occurred within the restorations (as seen in Figure 4). In this study luting cement is micromechanically connected to cavity walls. According of Vallittu *et al.* (2018) loads are not then distributed equally because of considerable differences in material properties and the interface between the components.[13] Discontinuity of load-displacement curves and crack formation in non-bonded samples are observed in Figure 2, which also refers to unequal stress distribution of non-bonded restorations.

The larger the adhesive interface and marginal adaptation of the restoration, the higher ultimate fracture load the tooth has. Proper bonding technique is a vital factor for survival of restored tooth as found in this study. Imperfect marginal integrity between dental tissue and restoration caused by i.e., undercut preparations for indirect restorations, could also lead to plaque accumulation, sensitivity, and secondary caries, which is why tight marginal seal between restoration and dental tissue is important. This study used a deteriorated bonding approach to imitate factors which cause disturbance in marginal sealing between dental tissue and restoration. For example, after saliva contamination bond strength is significantly

weaker. In enamel and dentine, microtensile bond strength and shear bond strength values are significantly lower in case of contaminated adhesion regardless of the adhesion method as has been reported in earlier studies.[21-28] Especially deep margins are susceptible to saliva contamination during the bonding procedure. Challenging cavity isolation during bonding, polymerization shrinkage of adhesive cement and other factors which deteriorate marginal integrity can complicate the bonding procedure. For indirect restorations, cavity geometry must be carefully considered. This study is in line with recent recommendations that in indirect restorations, tooth cavity internal angles should be rounded, and restorations properly bonded to increase the fracture resistance and lifespan of restored teeth.

Variations in natural teeth size, quality, and anatomy in this study create deviation in the test results. The bigger the tooth is, the stronger it is, however in this study, slight variation in cavity dimensions and wall thicknesses were not found to significantly affect the results. This may indicate that restoration bonding and cavity geometry are more influential factors considering restored tooth's strength in this study setup. In addition, microfractures may cause weaker fracture resistance as they promote initial fracture progress. Factors that caused variation in results were also occlusal morphology of the tooth and metal ball position on occlusal surface during the loading test. In some cases, metal ball position was not exactly in the middle of the occlusal surface of the restoration, which directed stress mainly to two cusps instead of all the cusps, although all restorations were designed to be as similar in occlusal surface as possible. Despite all the factors that caused variation, the most significant factors were bonding and cavity design. The importance of cavity design and restoration bonding in the loading strength of restored tooth was discovered, which was the purpose of this study. There appears to be no earlier studies using a similar setup, so more research is needed to compare both restoration cavity design and bonding effect on stress distribution and restored tooth fracture load. In the future, the effect of different bonding agents and different restorative materials and liners could be investigated with varying cavity designs to obtain more information about bonding methods and mechanical properties of materials and the relevance of cavity geometry on ultimate fracture load of the restored teeth.

CONCLUSIONS

According to this study, bonded restorations increase the loading strength of restored tooth. The findings of this study suggest that bonding has more influence on the strength of restored tooth compared to cavity bottom geometry, which had no statistical influence.

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