Finite element analysis for fracture resistance of reattached human tooth fragment with different types of retentive preparation techniques

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Objective: *Restoration of traumatized incisors by reattachment of the original tooth fragment appears to be the most conservative treatment approach. But the measurement of forces acting on natural tooth in-vivo poses many challenges. The advent of finite element analysis (FEA) has made it possible to demonstrate the propagation of stress through each part of a tooth and its restoration. The objective of this study was to evaluate and compare the fracture resistance of reattached human tooth fragment with different types of retentive preparation techniques using finite element analysis.* ***Study design:*** *An intact maxillary central incisor was obtained, scanned by laser and its Computer Assisted Device (CAD) model was generated and then converted to Finite Element Model (FEM). Mechanical properties of tooth specimen and materials were added on the generated mesh. These reattached fragments were then fractured with a force applied at 30°, 45°, 70° and 90° to the long axis of tooth. FEA Calculation was run with the setup.* ***Results:*** *The highest fracture strength recovery was found with internal dentinal groove (64.97%) followed by labial double chamfer with lingual over-contour (54.49%), subsequently by labial and lingual double chamfer (51.31%) and least was with simple reattachment (28.27%).* ***Conclusions:*** *Fracture resistance varied with different retentive techniques and greatest strength was offered by internal dentinal groove preparation.*

Keywords: *FEA, CAD, Internal dentinal groove, External double chamfer, Lingual over-contour, Fracture strength*

INTRODUCTION

Traumatic dental injuries are the most disruptive and distressing emergencies which are presented in the pediatric dental practice. A majority of fractures and injuries result from a simple fall or accidents which occur during sports activities, leaving patients in pain and discomfort [1]. The uncomplicated fracture of a crown is the most common type of traumatic injury affecting around 25% of the population under the age of 18 years [2]. In most cases, the group of upper incisors is affected because of the position and protrusion taken during the eruptive process. Restoration of such traumatized incisors by reattachment of the original tooth fragment appears to be the most conservative treatment approach [3]. Compared with other restorative techniques (composite restorations, laminate veneers and crowns), reattachment of fractured fragment can offer several advantages comprising improved aesthetics, function and restoration of the surface anatomy with increased wear resistance [4].

Clinical studies reported that the application of additional preparations, on both the fractured tooth and the fragment, before and after bonding, showed improved bond strength [5].

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The primary cause of failure of the reattached tooth fragment is new trauma or the use of the restored tooth with excessive masticatory forces[6].

Reis *et al.*[1] have reported that a simple reattachment with no further preparation of the fragment or tooth may not be able to restore even half of the fracture strength of intact tooth. Consequently, many authors have advocated the necessity of using additional preparations to augment the retention of the reattached fragment. Such preparation methods include internal dentin groove, external double chamfer, and the over-contour technique; all of which have their own advantages and disadvantages[7].

The structure of the human tooth and its supporting tissues is a complex assemblage of materials of varied mechanical properties. The direct methods of measuring surface stresses in actual teeth *in vivo* are associated with many and obvious problems because of the vitality of the tooth, its size and difficulties of access[8]. Classical methods of mathematical stress analysis are extremely limited in their scope and are inappropriate to dental structures that are of an irregular structural form and complex loading.

The finite element (FE) method, a modern technique which was originally introduced as a method for solving structural mechanics problems, FE analysis was quickly recognized as a general procedure of numerical approximation to all physical problems that can be modelled by a differential equation description. FE analysis has also been applied to the description of physical form changes in biological structures particularly in the area of growth and development and restorative dentistry[9]. Finite element analysis is applicable to solids of irregular geometry and heterogeneous material properties. It is therefore ideally suited for the examination of the structural behaviour of teeth (NISA training manual, EMRC, USA). Through finite element analysis, evidence can be gathered on the stress concentration areas along with the study of a single variable in a complex structure. The advent of finite element analysis has made it possible to demonstrate the propagation of stress through each part of a tooth and its restoration[9].

Various *in vitro* studies have been conducted comparing different techniques for fragment reattachment. However, the obtained results are within the limitations of the conventional methods which cannot simulate accurately the irregular form and the complex forces acting on a tooth. Thus in the current scenario finite element analysis provides the best option to study these complex loadings and can give us accurate results. Hence, this study was designed to evaluate and compare the fracture resistance of reattached human tooth fragment with different types of retentive preparation techniques using finite element analysis.

MATERIALS AND METHOD

An intact incisor was obtained from a 13-year-old boy reported to the clinic with oro-facial trauma and avulsed incisor within 30 min of avulsion. He had stored this tooth in tap water for 20–25 min. Patient had alveolar ridge fracture and suspected head injury requiring medical assistance, thus reimplantation was not considered for this patient. This incisor was then immediately stored in Hank's Balanced Salt Solution (HBSS) and within 3 days it was scanned for FEA analysis. It was first scanned by laser and its CAD model was generated. CAD Model was converted to FE Model. The finite element modelling is the representative of geometry in terms of finite number of elements and nodes. This process is called discretization. The main idea behind discretization is to improve the accuracy of the results. Physical and mechanical properties of tooth specimen and materials were added on the generated mesh (Table 1).

Table 1: Values of physical and mechanical properties of tooth used for FEA[10].

	Young's modulus (GPa)	Density (g/cm^3)	Poisson's ratio
Enamel	77.90	3.00	0.33
Dentin	16.6	2.20	0.31
Pulp	0.00689	1.00	0.45
Periodontal Ligament	0.05	1.10	0.45
Alveolar bone	3.50	1.40	0.33
Cortical bone	10.00	1.40	0.26
Cancellous bone	0.50	1.40	0.38

Each of these factors provided the software with data on to how a given material behaves when subjected to force application taking into consideration its deformation capacity, elasticity and behaviour under tension or compression. All the modelled groups were subjected to forces in different directions. The boundary conditions were defined to simulate how the model was constrained and to prevent it from free body motion. The nodes attached to the area of the outer surface of the bone were fixed in all directions to avoid free body movement of the tooth.

The tooth was then subjected to a force on the labial surface at a point 2 mm apical to incisal edge and 2 mm distal from mesio-labial line angle at 30°, 45°, 70° and 90° angulation to the long axis of the tooth to obtain a mesio-angular fracture involving enamel and dentin (the strength values were noted). Depending on the type of retentive preparations and reattachment of the tooth fragment, models were divided into 5 groups (Fig. 1).

Group A: Intact tooth (Control).

Group B: Simple reattachment—reattachment of the tooth fragment without any preparations.

Group C: Internal dentinal groove—a dentinal groove of 0.5 mm deep and 1mm wide in the fragment as well as on the tooth before reattachment was modelled and the space was occupied by the adhesive resin after bonding.

Group D: External double chamfer—after reattachment of fracture fragment, an external chamfer, 0.5 mm wide on the tooth and 0.5 mm wide in the fragment with a depth of 0.5 mm along fracture line of tooth was modelled and filled with adhesive resin.

Group E: Labial external double chamfer with lingual over-contour—after reattachment of fracture fragment, a labial external chamfer, 0.5 mm wide on the tooth and 0.5 mm wide in the fragment with a depth of 0.5 mm along fracture line of

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teeth and a lingual over contour of 0.3 mm deep extended for 2.5 mm coronally and apically from fracture line was modelled and then filled with adhesive resin.

The adhesive material and bonding agent were kept constant for all preparations. Hence, properties of Filtek Z250 resin as adhesive and single bond universal adhesive bonding agent were assigned (Table 2). These reattached fragments were then fractured with a force applied on the labial surface of reattached fragment at a point 2 mm apical to incisal edge and 2 mm distal from mesiolabial line angle at 30°, 45°, 70° and 90° to the long axis of tooth. FEA Calculation was run with the setup.

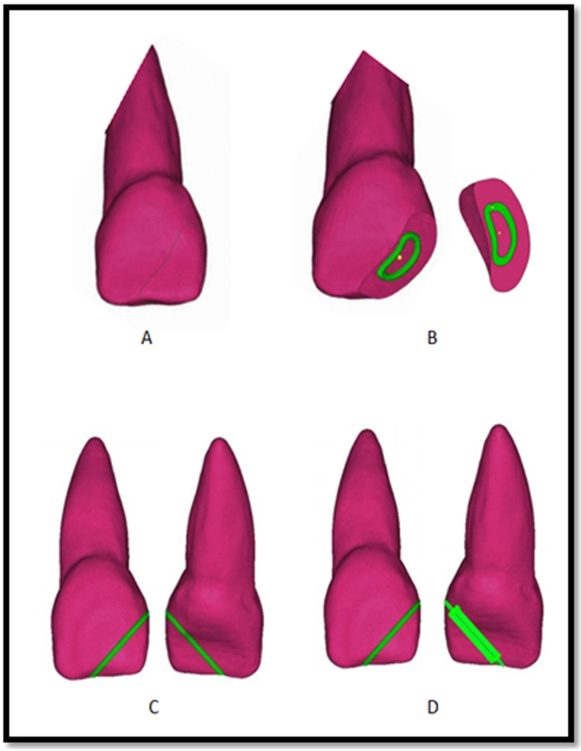

Figure 1: Various techniques used for fragment reattachment. A: Simple reattachment; B: Internal dentinal groove; C: Labial and lingual double chamfer; D: Labial double chamfer and lingual over-contour.

Table 2: Values of mechanical and physical properties of materials used in FEA [11].

Adhesive Material	Compressive strength (in MPa)	Flexural Strength (in MPa)	Modulus of Elasticity (in GPa)
Filtek Z250 (3M ESPE)	298.32	154.10	10.90
Bonding Agent	Shear Bond Strength (in MPa)		
Single bond	13.60		

RESULTS

After load applications on FE models, the images were obtained from the Finite Element Analysis. These images were colour graded such that dark blue represents areas experiencing minimal Von Mises stress and red represents areas experiencing maximal Von Mises stress. Fracture occurs when the Von Mises stress is generated within tooth enamel and dentin above their respective ultimate fracture strength. The force at which tooth fractures is depicted by red color, in the scale given alongside.

The intact tooth structure (Group A) showed strength of 311 MPa, 327 MPa, 314 MPa and 307 MPa under mechanical load at 30°, 45°, 70° and 90° angulations to the long axis of the tooth respectively, to fracture at enamel and dentin (uncomplicated fracture) (Table 3) & (Fig. 2).

Table 3: Fracture strength values (in MPa) at 30°, 45°, 70° and 90° angulations to the long axis of the tooth.

Groups	Stresses/Stength (MPa)			
	30°	45°	70°	90°
A	311	327	314	307
B	87	91	90	88
C	200	210	206	202
D	158	166	163	159
E	168	176	172	170

Simple reattachment of fractured fragment with the tooth using Filtek Z250XT and single bond universal adhesive bonding agent (Group B) showed the lowest fracture strength of 87 MPa, 91 MPa, 90 MPa and 88 MPa at 30°, 45°, 70° and 90° angulations to the long axis of the tooth respectively (Fig. 3). The fracture strength recovery in this group was only 28.27%. The Group C *i.e.* reattachment of fractured fragment using Filtek Z250XT and single bond universal adhesive bonding agent with internal dentinal groove preparation on both fragment and tooth showed maximum fracture strength recovery (64.97%). This group showed fracture strength of 200 MPa, 210 MPa, 206 MPa and 202 MPa at 30°, 45°, 70° and 90° angulations to the long axis of the tooth respectively (Fig. 4). The fracture strength of remaining two groups lied between Group C and B. The Group D in which tooth fragment was reattached and external double chamfer preparation filled with Filtek Z250 and single bond universal adhesive bonding agent showed fracture strength of 158 MPa, 166 MPa, 163 MPa and 159 MPa at 30°, 45°, 70° and 90° angulations respectively to the long axis of the tooth (Fig. 5). The mean fracture strength recovery was 51.31%. The Group E in which the tooth fragment was reattached, labial double chamfer and lingual over-contour preparation was filled with the Filtek Z250 and single bond universal adhesive bonding agent showed 168 MPa, 176 MPa, 172 MPa and 170 MPa fracture strength at 30°, 45°, 70° and 90° angulations respectively to the long axis of the tooth (Fig. 6). The fracture strength recovery was 54.49%. The mean fracture strength recovery in descending order was Group C > Group E > Group D > Group B (Table 4).

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Table 4: Fracture strength recovery (in %) at 30°, 45°, 70° and 90° angulations to the long axis of the tooth.

Groups	Fracture Strength Recovery (%)				
	30°	45°	70°	90°	Average
A	–	–	–	–	–
B	27.97	27.82	28.66	28.66	28.27
C	64.30	64.22	65.60	65.79	64.97
D	50.80	50.76	51.91	51.79	51.31
E	54.01	53.82	54.77	55.37	54.49

DISCUSSION

Coronal fractures of anterior teeth are the most frequent form of dental injury and they represent 18–22% of all traumas to dental hard tissues of which, 96% involve maxillary incisors, hence maxillary central incisor was modeled in the present study.

Numerous techniques developed overtime have all involved the sacrifice of healthy tooth structure and hence with the development of adhesive dentistry, fragment reattachment, an essentially conservative approach is being utilized to treat coronal fractures of anterior teeth [12]. For quantitative fracture analysis of tooth, the mechanical method does not represent the realistic model. Hence, 3D FEM models were generated for our study as they provide more reliable data which is more accurate [13]. The FEM has been used extensively in dental biomechanics research. The method is powerful and versatile in that it can provide detailed information on stresses, strains, and displacements within complex structures such as teeth [14].

The human tooth is neither planar nor symmetrical. Hence, the loading on the tooth is neither in a state of plane stress nor is symmetrical [15]. 3D models, in turn, are more complex but allows a complete assessment of structures and loads, in any direction. The cushioning effects on strain energy dispersion by periodontal ligament and the pulp cannot be ignored for tooth-trauma analysis. Therefore, the damping properties of the tooth should be considered which was taken from the previous studies [16]. As the FEA produces a virtual geometric model of a structure with all its inherent properties through given values using nodes and mesh work, the same object under study can be used as many times as possible. Thus, only one intact tooth was used for all the groups in the present study.

The least fracture strength recovery in simple reattachment can be attributed to the smallest surface area available for bonding. Also, the interface had the least amount of adhesive used for reattachment. Simple reattachment does not provide any additional retention for strong bond. The fracture line is also not masked in this technique posing the esthetic inferiority. The probable reason for external double chamfer to show a higher value when compared to simple attachment might be due to the reinforcement of the reattachment by preparing a chamfer adjacent to the fracture line and restored with resin composite. The removal of the aprismatic superficial enamel layer which is richer in fluoride content favors the acid etching and increases the free surface energy. It favors surface wetting and enhances the surface area of exposed enamel. It also tends to improve the material retention. However, this cannot be incorporated in FE models. It provides better marginal seal; better esthetic results and makes it difficult to detect the interface. Also, the greater the extension of material on that surface, the better the force distribution over a large enamel area and the higher toughness of resin composite placed on the labial surface is likely to absorb the fracturing load applied to the tooth before its failure [17].

In the present study tooth model in group D (External double chamfer technique) and in group E (combined double chamfer and over-contour technique) presented a fracture strength recovery more than 50% that of the intact tooth. This could be attributed to the increase of the surface area of adhesion after the preparation of the tooth in the region of the fracture line. The tooth model in group E obtained results of resistance against fracture superior compared to group D, possibly because of the lower amount of dental structure removed during the preparation of the lingual surface and overcontoured by resin on this surface. This could be important from a clinical point of view, since at an equal value of esthetics, a more conservative preparation of the lingual surface is able to enhance the strength of whole restoration. Reis *et al.* [1] highlighted that the resistance of the restored dental elements with chamfer technique was equal to 60.6% of that of the whole tooth, while the resistance of teeth restored by the use of over-contour was equal to 97.2%. However, the removal of enamel and its subsequent covering with a filled resin renders the restoration to chromatic alterations when these materials are exposed to the oral cavity [18].

The dentinal grove preparation was done 0.5 mm deep and 1 mm wide in both fractured fragment and the tooth, the highest fracture strength recovery with internal dentin groove can be due to utilization of a greater volume of resin which created a continuous intact bar and opposes the forces applied on the labial surface. This continuous bar provides the cushioning effect and distributes the forces acting on it and dispenses higher fracture resistance. The groove is prepared in dentin of the fragment and also the tooth, leaving sufficient amount of dentin for pulp protection. It is a skilled procedure and also technique sensitive. However, it is clinically possible to use this technique even in young permanent tooth [19–21]. If the clinician anticipates pulp exposure due to proximity of fracture line to pulp or less dentin thickness, then this groove preparation can be restricted only to the fractured fragment.

CONCLUSIONS

Within the confined limitations of FEA, in the given framework the following conclusions can be made; Fracture strength recovery (Fracture Resistance) of reattached teeth fragments in different groups showed a large variation from 27.82% to 65.79%. The uncomplicated crown fracture of a tooth can be successfully managed by tooth fragment reattachment with various retentive preparations techniques with their own advantages. The highest fracture strength recovery was obtained by internal dentinal groove preparations filled with Filtek Z250 resin and single bond universal adhesive bonding agent, compared to simple reattachment, external double

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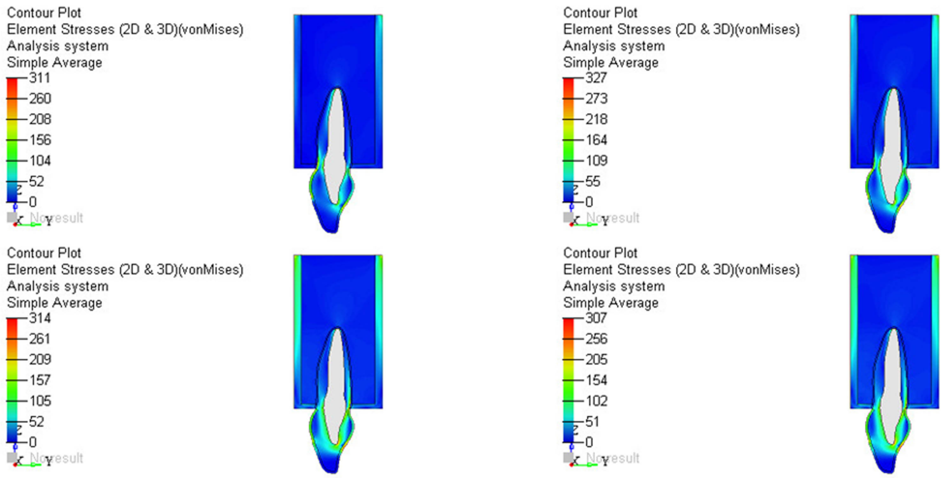

Figure 2: Group A. Fracture strength values (in MPa) of intact tooth at 30°, 45°, 70° and 90° angulations.

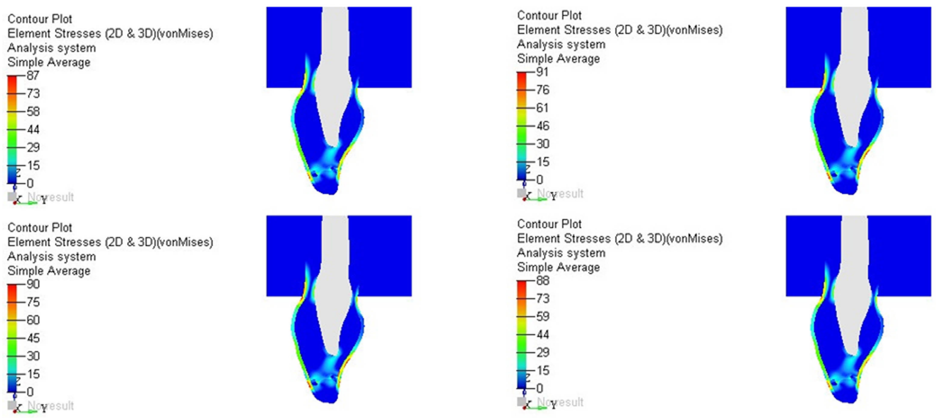

Figure 3: Group B. Fracture strength values (in MPa) by Simple reattachment of tooth fragment with Filtek Z250 at 30°, 45°, 70° and 90° angulations.

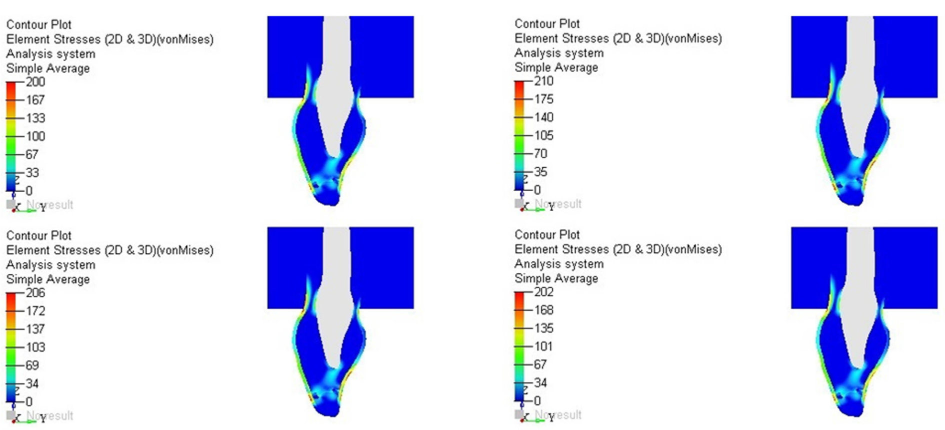

Figure 4: Group C. Fracture strength values (in MPa) of tooth fragment at 30°, 45°, 70° and 90° angulations reattached by internal dentinal groove preparation technique.

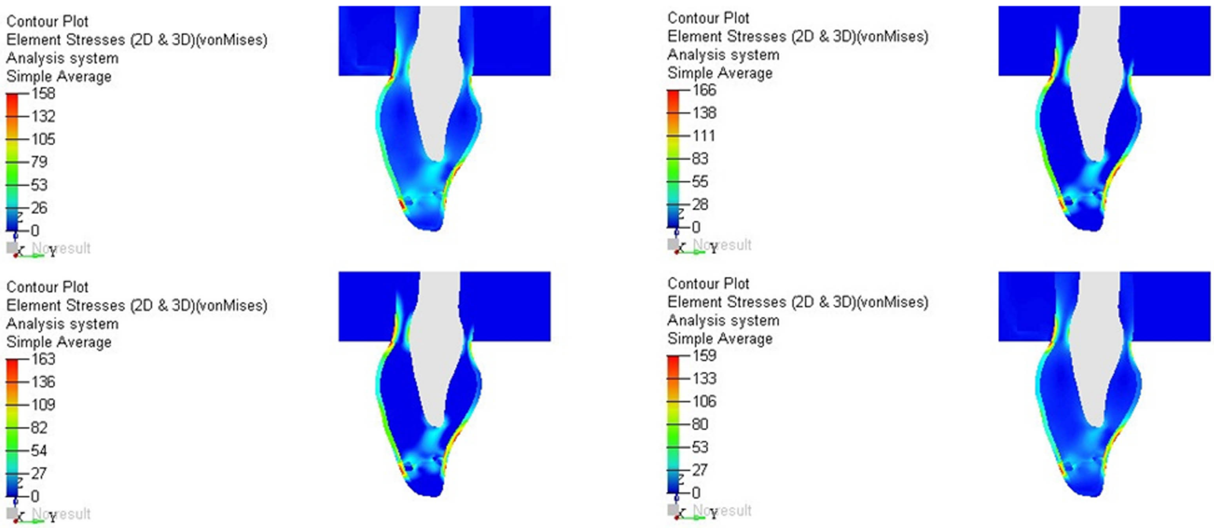

Figure 5: Group D. Fracture strength values (in MPa) of tooth fragment at 30°, 45°, 70° and 90° angulations reattached with labial and lingual chamfer technique.

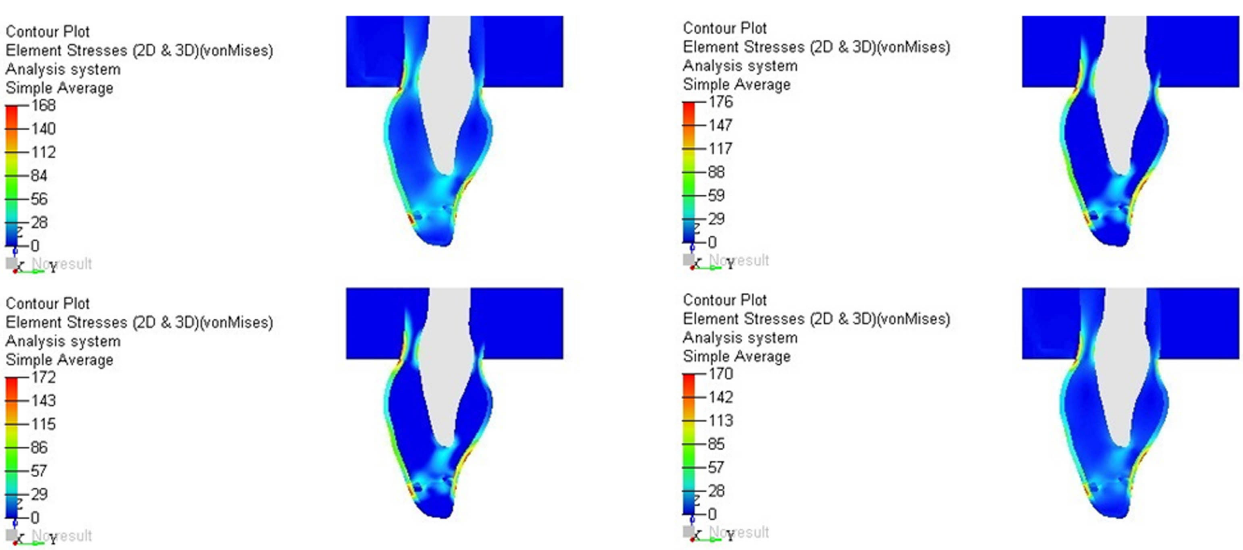

Figure 6: Group E. Fracture strength values (in MPa) of tooth fragment at 30°, 45°, 70° and 90° angulations reattached by labial chamfer and lingual over-contour preparation technique.

chamfer and labial external double chamfer with lingual overcontour preparations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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