# Stress distributions of a bracket type orthodontic miniscrew and the surrounding bone under moment loadings: Three-dimensional finite element analysis

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## ABSTRACT

**Objectives:** To evaluate the effect of moments and the combination of forces and moments on the mechanical properties of a bracket type miniscrew, resembling engagement of a rectangular wire by three-dimensional (3D) finite element study.
**Materials and Methods:** By solid work software (Dassaunlt systems solid works, concord, Mass), a 3D miniscrew model of 6, 8, 10 mm lengths was designed and inserted in the osseous block, consisted of the cortical, and cancellous bones. The stress distributions, maximum stresses, and deflections of the miniscrew were evaluated for all parts using ANSYS (Work Bench, 2014).
**Results:** As the magnitudes of the load increased from 100 to 200, 400 and 800 grf-mm, the peak of stresses in the 6 mm long miniscrew were increased from 7.7 to 61.5 Mpa. The maximum values of Von Mises in the cancellous bone were tremendously lower in comparison to the cortical bone by one hundredth. As the length of the miniscrew in contact with the bone was increased, the amounts and patterns of stress distribution in the cortical bone and the miniscrew did not change significantly.
**Conclusions:** As the moment magnitude increased, the pick stresses increased linearly. The existence of cancellous bone was not significantly responsible for the stress distribution. The pattern of stress distribution did not change by the length of the miniscrew.


**Key words:** Finite element, force, miniscrew, moment, orthodontic

## INTRODUCTION

Anchorage consideration is an important factor in a successful orthodontic treatment. Sometimes, a stationary anchorage with no movements is the ideal, and the orthodontic miniscrews can provide such an anchorage for us.[1,2] Furthermore, it is introduced as an effective stationary anchorage device requiring no patient compliance.[3] The interdental types of miniscrews have become increasingly popular because of their biocompatibility, easier surgical procedures, less trauma during insertion and removal, immediate loading after implantation, and lower cost.[3] They have been improved in terms of designs and materials in the past 20 years. Their failure rates are ranging from 10% to 30% in most cases.[4] As a result, the mechanical properties of those devices in applying diverse force systems need to be evaluated.[3,5]

Some factors are associated with clinical failures of these interdental miniscrews. The influential factors for the primary stability of the miniscrews include patient's age,[5] cortical bone's thickness and qualities,[6] implant sites,[7,8] miniscrew designs

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and materials.[9] Although immediate loading of these implants makes their primary stability greatly important, types of tooth movements and level and type of force application on the miniscrews could also affect the failure rates of these devices during their applications. They may even extrude or tip under orthodontic loadings.

Finite element studies on stress distributions of the orthodontic miniscrews by Dalstra *et al*. and Gallas *et al*. revealed that areas of maximum stress were at the neck of the miniscrews.[7,10] Although the conical shapes of the miniscrews could have a better primary stability in comparison to cylindrical ones, excessive insertion torque might be considered a problem.[8] Various mini-implants design factors, including thread depth, degree of tapering and length were investigated, and using finite element analysis. The miniscrews with greater thread depth, smaller taper degrees and shorter taper length generated higher maximum stress on the bone and the thread elements. The clinical areas of stress on the loaded miniscrews were at the top of threads in the upper 2.5 mm of cortical bone.[3]

Moreover, different types of loading can impact the pattern of the stress distribution in the miniscrews and the surrounding bone. Two types of loadings, horizontal, and torsional were applied. The maximum stress values and sites were slightly different between the two types horizontal and torsional loadings.[11] The effects of different force directions on the stress and displacements of miniscrews were evaluated and the highest stresses were produced, when the force was perpendicular to the long axis of the miniscrews.[12] Bracket types of interdental miniscrew can be applied to change the root torque, extrude, and even buccal tip a single tooth or a segment of teeth if a couple force was inserted in the rectangular auxiliary wire engaging the slot of the bracket type miniscrew.[13] They also can be used as a stationary anchorage for tooth movements by the wire using some types of closing loops, engaging one end of the wire in the miniscrew, and at the same time applying the proper torque both of which means combination loads of single force and moment on the bracket type of interdental miniscrews. These types of loadings; moment and the combination of moment and single force, is needed to be investigated base on their impacts on the mechanical properties and stress distributions in the bracket type miniscrews and the surrounding bone. As a start, this study was designed to investigate these effects using a finite element study.

## MATERIALS AND METHODS

The finite element analysis is a computer assisted method which evaluates biomechanical responses to different types of loading under precise control of the parameters. This method divides a complex design into a number of simpler elements.[10]

A three-dimensional miniscrew integrated in a bone block was constructed using a computer-aided program, solid works (Dassault systems solid works, concord, Mass). The dimensions for the miniscrew model were obtained from the study by Singh *et al*. who used a microscopic tool marker (Mitutoyo, Bengaluru, India) with an accuracy of 10 mm to measure an actual conical self-drilling miniscrew implant (SK surgical, Ambegan, Pane, India).[12] The dimensions for different parts of the miniscrews were as follows: The total length was 10.6 mm with a shaft length of 6.8 mm. Diameters were 2.4 mm at the head, 0.95 mm at the upper end, and 0.8 mm at the lower end of the shaft with tapering angle of 0.37°. There was also a sharp pyramidal apex with 0.15 mm in height at the tip of the miniscrews. All dimensions of the designed miniscrews are shown in Figure 1a.

The models were imported to the finite element software (Work Bench, 2014). The osseous block which surrounded the miniscrews consisted of cortical and cancellous bones with dimensions of 20 mm in length and width, and 15 mm in height. The cortical bone thickness was considered 2 mm for the purpose of the analysis and the rest of the osseous block was made up of cancellous bone.

The model was meshed with tetrahedral elements using workbench mesh generation tool. Table 1 shows the number of nodes and elements for miniscrews of different lengths [Figure 1b]. In all cases the maximum skewedness of the mesh is 0.89, and the maximum aspect ratio is 9.98.

The contact model was based on the result of the study by Liu *et al*.[11] in which as the force acting on miniscrew was increased by 2 times, the resulting stress and deflection in miniscrew were also increased by 2 times. This shows that the area would not change during the application of load. Therefore, selecting the bonded type for all contacts is considered as a good choice.

All materials assumed to be homogeneous, isotropic, and linearly elastic in all dimensions. Both miniscrews were

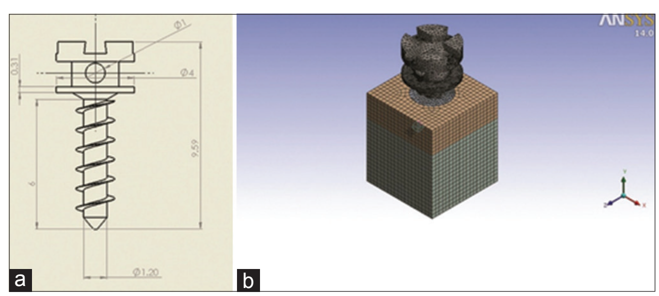


**Figure 1:** (a) Design of the bracket type miniscrew with detailed dimensions; (b) meshed finite element model demonstrating the miniscrew placed in the bone block

**Table 1: Number of nodes and elements at different lengths ofthe miniscrew**

| Length (mm) | Number of nodes | Number of elements |
|---|---|---|
| 6 | 471641 | 305726 |
| 8 | 525323 | 340564 |
| 10 | 579034 | 386695 |

considered to be pure titanium. The Young's modulus and Poisson's ratio for every part of the model are demonstrated in Table 2.

Multiple load condition was applied on both designs: The moment loads of 100, 200, 300, 400, and 800 grf-mm the combination loads of the mentioned moments, and the horizontal forces of 100 and 200 grf [Figure 2].

As the final step, all the variables of stress distribution, maximum stress, and deflection were evaluated for all parts of the designed miniscrews, also for the bone block, using the ANSYS software.

## RESULTS

In this study, the focus was on the impact of different loading types on a bracket type interdental titanium miniscrew and the data were evaluated using ANSYS (WorkBench Software, 2014). Von Mises criterion was applied to determine the distribution of stress in the miniscrew and the surrounding osseous structures. The units for all values of stress were Mega Pascal defined as Newton's per square mm, and the displacement values were in mm. The maximum stress and displacement in different types of loading conditions were evaluated which are tabulated and shown in Figures 3-5.

Patterns of stress distribution in a 6 mm long miniscrew under the moment loads were as follow. With 100 grf-mm moment, the area of maximum stress was located at the top of the neck of the miniscrew and gradually decreased toward the apex. As

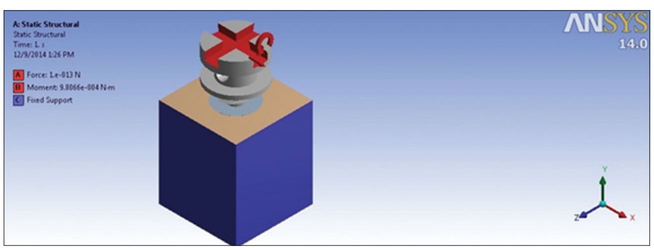


**Figure 2:** Boundary and loading condition for a moment load. Boundary and loading condition for a combinational load of a moment and a horizontal load

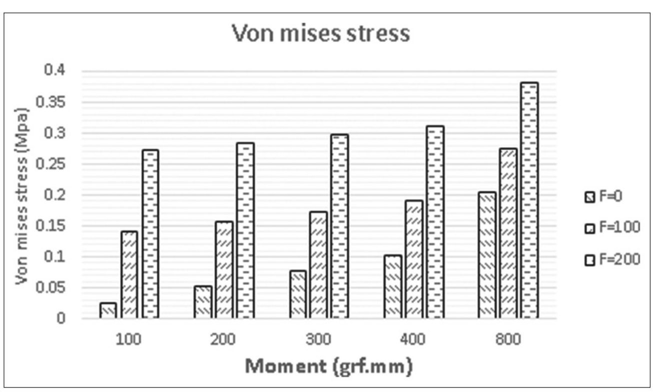


**Figure 4:** Stress (Mpa) values for the 6 mm long miniscrew model under load for cancellous

the magnitude of the load increased from 100 grf-mm to 200, 400 and 800 grf-mm, the peaks of stress in the 6 mm long miniscrew were increased with linearly proportion ranging from 7.7 Mpa to 61.5 Mpa [Figure 3, green color code].

The maximum values of Von Mises in the cancellous bone were tremendously lower in comparison to values of the cortical bone by one hundredth [Figure 4]. However, the peak Von Mises stresses on both the cortex and the cancellous bone were linearly proportional relative to the moment magnitudes in the 6 mm long miniscrew ranging from 2.5 Mpa to 19.9 Mpa for the cortical bone and 0.025 Mpa to 0.205 Mpa for the cancellous bone [Figures 3,4, and 6].

The amounts of deflection in the 6 mm long miniscrew were as follow. The greatest amount of deflection (0.006 mm)

**Table 2: Mechanical properties of the material used for the investigation**

| Material | Poisson's ratio | Young's modulus (MPa) |
|---|---|---|
| Implant-graded Titanium | 0.33 | 205,000 |
| Cortical bone | 0.3 | 13,700 |
| Cancelleous bone | 0.3 | 1,370 |

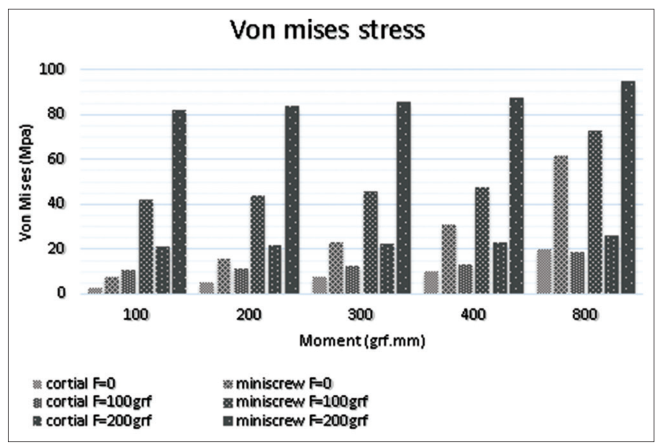


**Figure 3:** Stress (Mpa) values for the 6 mm long miniscrew model under load for cortial and miniscrew

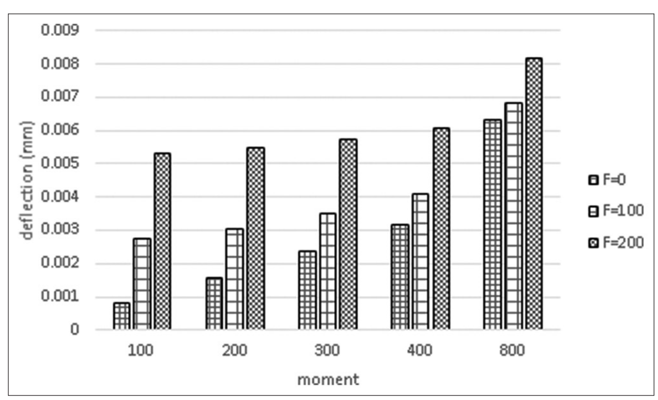


**Figure 5:** Miniscrew deflection (mm) values for the 6 mm long miniscrew model underload

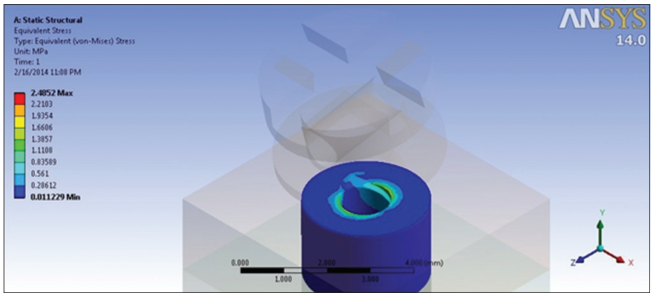


**Figure 6:** The amount of Von Mises stress in the cortical bone under 100 grf-mm moment loads

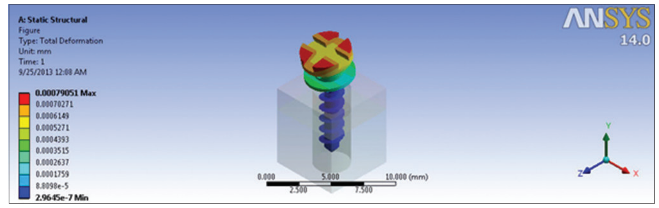


**Figure 7:** Displacement patterns in a bracket type miniscrew model under 100 grf-mm moment load. Color coding depicts the greatest displacement at the head of the bracket (Red) with lowest amount of displacement in the bone anchored area of the miniscrew (blue). Color coding shows the maximum stress in the cortical bone around the neck area of the miniscrew

was seen at the top of the head of the 6 mm long miniscrew [Figures 5 and 7]. The relation between the moment magnitudes and the maximum displacement of the 6 mm miniscrew were similar to the ones reported for the peak Von Mises stresses. As the moment magnitudes increased, the greater displacements of the miniscrew were seen [Figures 5 and 7].

Applying an additional force of 100 grf and 200 grf on the 6 mm miniscrew, simultaneously along with the exerted moments, the peak Von Mises stresses were increased in all parts. Comparing the groups with and without additional forces, some remarkable differences were observed [Figure 3, violet and red color codes]. The additional forces increased the maximum Von Mises stresses slightly. The greatest amount of stress (99.2 Mpa) was reported in the neck of 6 mm long miniscrew when applying a transverse force of 200 grf in combination with an 800 grf-mm moment [Figure 3]. The normalized results are also shown in Table 3.

As the length of the miniscrew in contact to the bone and thus, the overall length of the miniscrew was increased, the amounts and patterns of stress distribution in the cortical bone and the miniscrew did not change significantly. However, the amount of Von Mises stress in the cancellous bone demonstrated a marginal increase. The relativity linear results come from the fact that all problem specifications are linear [Figure 8].

## DISCUSSION

Due to limited index for mechanical measurements and difficulties in unifying the samples for experimental approaches, finite element analysis affords a better approach to understand the mechanical properties of the miniscrew applications in orthodontics.[11]

Any mechanical indices can be analyzed precisely anywhere in the models. However, the mesh algorithm model can impact the results of the study. In this study, the models consisted of 471,641 Nodes and 305,726 elements for the 6 mm long miniscrew. The bone block was considered rectangular, and various nodes in the area surrounding the bone block were fixed in all degrees of freedom. All the materials were supposed to be homogenous and linear. The miniscrew was in contact with

**Table 3: Normalized data to compare the maximum Von Mises stress (Mpa) and displacement at different loading conditions**

| Moment (grf-mm) | Moment + force (grf-mm + grf) | Stress (Mpa) | | | Deflection (mm) |
|---|---|---|---|---|---|
| | | Cortical bone | Cancellous bone | Miniscrew | Miniscrew |
| 100 | - | 1.00 | 1.00 | 1.00 | 1.00 |
| 200 | - | 2.00 | 2.00 | 2.00 | 2.00 |
| 300 | - | 3.00 | 3.00 | 3.00 | 3.00 |
| 400 | - | 4.00 | 4.00 | 4.00 | 4.00 |
| 800 | - | 8.00 | 8.00 | 8.00 | 8.00 |
| - | 100+100 | 4.36 | 5.52 | 5.43 | 3.46 |
| - | 200+100 | 4.65 | 6.06 | 5.67 | 3.85 |
| - | 300+100 | 4.95 | 6.71 | 5.91 | 4.44 |
| - | 400+100 | 5.25 | 7.42 | 6.16 | 5.16 |
| - | 800+100 | 7.60 | 10.70 | 9.49 | 8.66 |
| - | 100+200 | 8.42 | 10.58 | 10.62 | 6.71 |
| - | 200+200 | 8.71 | 11.04 | 10.86 | 6.91 |
| - | 300+200 | 9.01 | 11.55 | 11.10 | 7.25 |
| - | 400+200 | 9.30 | 12.13 | 11.34 | 7.70 |
| - | 800+200 | 10.50 | 14.85 | 12.33 | 10.33 |

the bone. Hence, the stress of insertion was neglected in the assembly before the external loading.[12]

This type of analysis also has its own limitations in simulating the reality. As stated by Gracco *et al*. the bony tissue behaves as a viscoelastic material, and the insertion stress in the field would be relaxed.[14] In addition, the miniscrew was inserted at the right angle to the bone which did not imitate the intra-oral situation. These certain assumptions were needed to facilitate the process of analyzing.

### The Impact of Loadings on the Bone

The results of this study on applying moments on the bracket type miniscrew were similar to the study done by Dalstra *et al*. and Gallas *et al*. who reported that the maximum stresses were put on the cortical bone which surrounded the neck area and which applied a single perpendicular force relative to long axis of the miniscrew.[7,10]

Even for torsional loading as was shown in a study conducted by Single *et al*., the maximum stress in the cortical bone

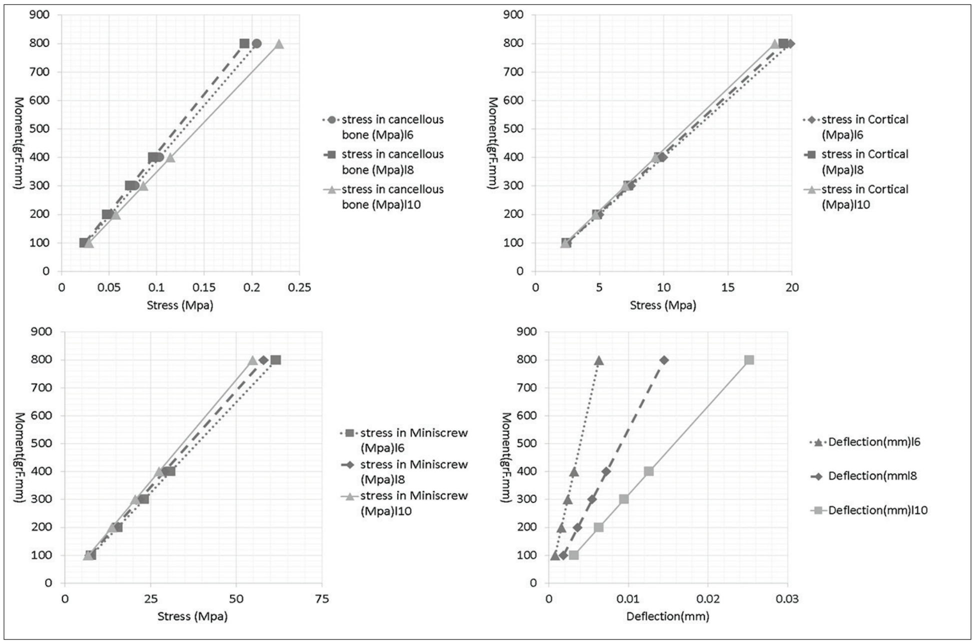


**Figure 8:** Comparison of stress (MPa) and displacement (mm) values for different lengths of miniscrew models under different types of loading

was 8.5 Mpa. This study also showed 2.4, 4.9, 7.4, 9.9, and 19.8 Mpa for 100, 200, 300, 400, and 800 moments, respectively.[11] The amount of maximum stress was significantly lower in the cancellous bone which was similar to the results by Singh *et al*.[12] and confirmed by Suzuki *et al*.[12,14,15]

It can be concluded from the obtained data that the existence of the cancellous bone did not significantly impact the maximum stress and that the cortical bone is mostly responsible for absorbing the stresses. Even when we combined the maximum moment of 800 grf-mm with 200 grf at the same direction the greatest amount of Von Mises for the cortical bone was 42.8 Mpa, which is almost one-third of the yield strength of 122 Mpa for the cancellous bone.

As stated by Liu *et al*., increasing the depth of the implanted screw is not the dominant factor for the amount of Von Mises stress value in the cortex bone.[11] This is in agreement with our results even though the type of loadings was different for the two studies.

## The Impact of Loadings on the Miniscrews

The greatest amounts of Von Mises stress on the 6 mm long miniscrew were concentrated in the neck area. The pattern of stress distribution did not change when the length of the miniscrew and/or the amount of the applied moments was increased.

These patterns of stress distribution are consistent with those of Single *et al*. and Gracco *et al*. who pointed to the neck of the miniscrew as the area bearing the greatest amount of Von Mises stress, even though their type of loadings were different.[12,14] As concluded by Single *et al*., to prevent such a bending, the width of the neck area should reach the width of the head region. Furthermore, the holes in the center of the screws which are necessary for the purpose of tying should be as small as possible to hinder the fracture, especially for the bracket type miniscrews when applying the moments.[12] In contrast to the results by Gracco *et al*., the short miniscrews of 6 mm and 8 mm endures almost the same amount of maximum Von Mises as the 10 mm long minscrew.[14]

The bending mode of the loaded miniscrew in the current study is pure bending and each cross section of the miniscrew, from one end to the other, undergoes the same amount of bending. On the other hand, transverse loadings which were applied in other studies did not produce uniform stress along the miniscrews, if they were considered cylindrical. However, in taper miniscrews the situation is vice versa which would explain why Gracco *et al*. result is in contrast with the result of this study.[14] When the diameter of the miniscrew differs along its length, applying a transverse bending versus a pure bending such as moment, leads to similar amounts of stress in all cross sections.

The results of Finite Element Analysis are in a static condition. Considering the Mechanostat concept of frost, if the peak srtain exceeds 4000 microstrain, it leads to a pathologic fracture. As a result, the amount of strains resulted from loading may be a better criterion to evaluate the impact of loadings on the bony structures. Therefore, we propose that it is better to also calculate the strain in the bone which is needs to be evaluated in the future studies.[16] It should be considered that in the clinical situation the force is not constant and are mostly intermittent, as the result, the miniscrews should not considered in a static condition. Their loading condition would change between visit intervals which would impact the clinical results.

## CONCLUSIONS

According to the findings of this study, we can conclude that: First, as the moment magnitude increased from 100 grf-mm to 800 grf-mm, the pick stresses increased linearly. Second, the Von Mise stress of applying the maximum moment of 800 grf-mm in combination with 200 grf was below the yield strength of the cortical bone. Third, the existence of the cancellous bone did not significantly impact the maximum stresses; the cortical bone was mostly responsible for such an impact. Finally, it should be noted that the current study was a 1 time evaluation which could not be entirely extrapolated to the oral environment because the implant displacement under an orthodontic load should be considered a progressive process. Since the results of this study and similar studies show linearity response to load by means of superposition theorem and also by using Mohr circle to find maximum stress and displacement, one can estimate the results based on the results obtained for a specific miniscrew.

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### Conflicts of Interest

There are no conflicts of interest.

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